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RESULTS OF THE SOLAR CELL EXPERIMENTS ABOARD THE NTS-2 SATELLIT--ETC(U)
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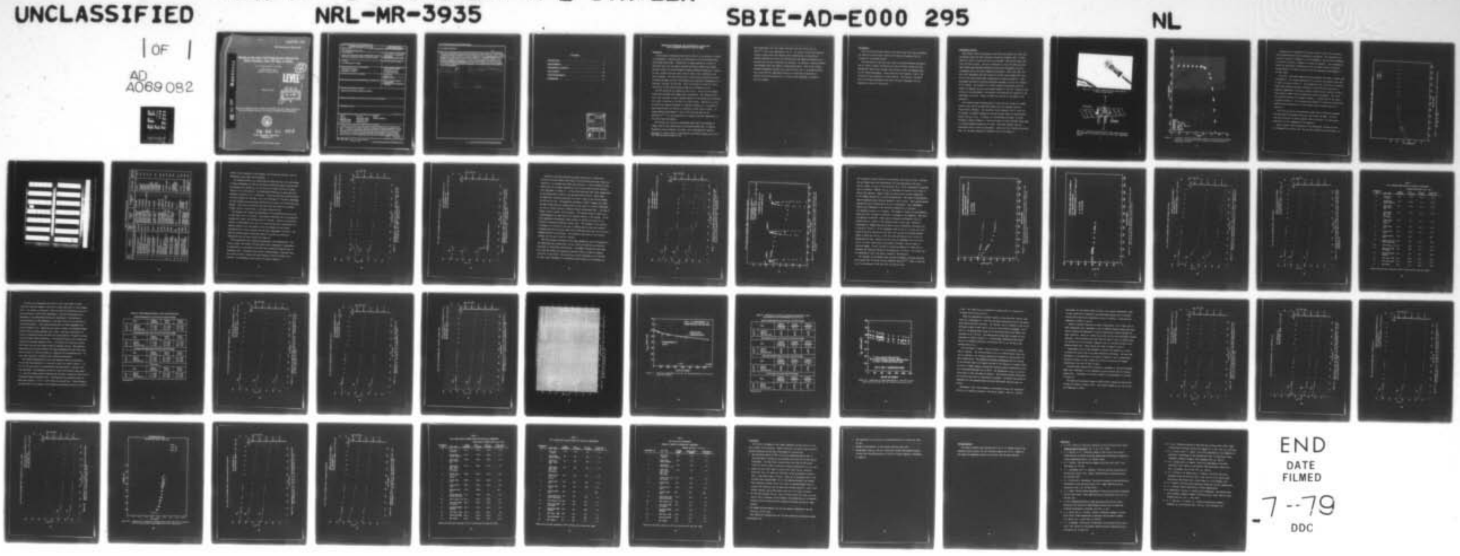

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NRL Memorandum Report 3935

Results of the Solar Cell Experiments Aboard the NTS-2 Satellite After 447 Days in Orbit

D. H. WALKER AND R. L. STATLER

Radiation Effects Branch
Radiation Technology Division

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LEVEL III

March 9, 1979

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NTS-2	I-V curve	Satellite
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Photovoltaic cells	Maximum power	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results after 447 days in orbit of the solar cell experiments aboard the NTS—2 satellite are presented. The objective of the solar cell experiment, consisting of 15 separate experiments of five cells each, is to evaluate the performance of state-of-the art solar cells in the space environment. Telemetered data from the 14 silicon and one gallium arenside modules indicate a more severe radiation environment in the 63 degree, 20, 190 km circular orbit than was predicted. Based on the NTS—2 data, the solar power array containing Spectrolab Helios cells will degrade 27 ~~percent~~ % in maximum

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20. Abstract (Continued)

power over the three-year mission. Solar cell panel temperatures have reached 104 C providing ideal conditions for annealing of the radiation-induced damage in the gallium arsenide cells. After 15 months of operation these cells have suffered the least power degradation, with a maximum power loss of 14.0 % ~~percent~~. After 447 days in orbit, the loss in power ranged from 14.0 ~~percent~~ to 59.5 percent with the exception of the Solarex "low-cost space cell" which became open-circuited on the 69th day. The average value of I_{sc} measured in space on the first day of exposure agreed with prelaunch solar simulator values to within 1.41 ± 0.99 percent. The agreement between V_{oc} in space and solar simulator values was 1.24 ± 1.08 percent. Results are summarized of the changes in the photovoltaic parameters of each of the experiments.

%

V sub oc

1 + or - 0.99%.

I sub sc

1.24 + or - 1.08%.

CONTENTS

RESULTS OF THE SOLAR CELL EXPERIMENTS ABOARD THE NTS–2 SATELLITE AFTER 447 DAYS IN ORBIT

Background

The Navigation Technology Satellite-Two (NTS-2) is the second in a series of developmental satellites that are forerunners of the DoD NAVSTAR Global Positioning System (GPS). NAVSTAR GPS is being developed as a group of satellites that will use passive ranging techniques combined with highly accurate clocks to provide extremely accurate navigation capability to ships, aircraft, ground forces and other users 24 hours a day, worldwide in any kind of weather. The GPS satellites will occupy various positions in orbit affording extremely accurate three-dimensional navigational information, i.e., longitude, latitude, and altitude. NTS-2 was launched 23 June 1977 into a twelve-hour circular orbit 20,192 km high at an inclination of 63°.

The GPS satellites are powered by solar cells. Every year the demands become more stringent with higher power requirements. The radiation which solar cells encounter in space produces defects in the semiconductor materials that cause a reduction in the solar cell power output. Therefore, in order to predict the expected lifetime of a satellite mission, it is necessary to know quantitatively the effects of radiation on solar cells in space. Although numerous measurements of solar cells have been made in the laboratory,[1-10] it is more significant to observe solar cell degradation in the actual space environment.

The fifteen (15) solar cell experiments aboard NTS-2 are designed to compare initial space performance with prelaunch ground data, to measure degradation rates throughout the flight, and to determine the radiation resistance of several types of experimental and advanced design solar cells.

Note: Manuscript submitted December 21, 1978.

These experiments will also answer questions that have arisen from the NTS-1[11-13] solar cell experiments, such as: the need for ultraviolet rejection filters in space solar cell systems, space qualification of electrostatic bonding techniques for solar cell coverslips and the improved efficiency to be realized from the use of textured cell surfaces. In addition, a gallium arsenide (GaAlAs/GaAs) solar cell module is being flight tested. Each of the fifteen separate experiments consists of an array of five 2 cm x 2 cm state-of-the-art solar cells with all experiments linked to an electronics package which measures the entire photovoltaic I-V curve of each experiment in sequence every two minutes.

Requirements

This is the first annual report on the NTS-2 solar cell flight experiments and covers the period from 1 October 1977 through 30 September 1978 as requested by the program monitor.

The major goals of the past year's work at the Naval Research Laboratory were to reduce, correct, and analyze the data to provide a history of the temperature, open-circuit voltage, short-circuit current and maximum power for all fifteen experiments. These goals have been achieved. Some of the results have been forwarded in interim reports. The results of the NTS-2 solar cell flight experiments from launch through 30 September 1978 are summarized in detail in this report.

Experimental Results

This report covers the analysis of data from the fifteen (15) solar cell experiments aboard the NTS-2 satellite through 30 September 1978. To date twenty-two selected revolutions have been analyzed. This period covers the first 447 days in orbit. Day one is reckoned as 7 July 1977 when the solar power paddles were deployed exposing the solar cell experiments to solar illumination and to the total radiation environment. Until that time, the solar cell experiments had been covered by the main array paddles that were still in the wrap-around launch configuration as shown in Figure 1a. That arrangement provided an effective shielding thickness of 40 mils of aluminum (0.274 gm/cm^2). The satellite is rotated around the appropriate axis, as needed, to maximize the solar cell paddle exposure to the sun. Because of the location of the experiments, this maneuver also maximizes the exposure of the experiments to the sun. Figure 1b shows the location of the panels on the spacecraft.

The current-voltage characteristics of the solar cell arrays are telemetered in real time as the satellite passes over the tracking station at Blossom Point, Maryland. The electronic circuit measures the I-V curve for each module in sequence reading out current-voltage values for evenly-spaced points from I_{sc} to V_{oc}. A typical I-V curve showing the number of points obtained is shown in Figure 2. Each cell module is short-circuited except when it is being stepped through the I-V curve. Data were obtained from the experiments within 6 hours of deployment. During the first recorded revolution (Rev. 31) the panel temperatures measured close to 60 degrees C.

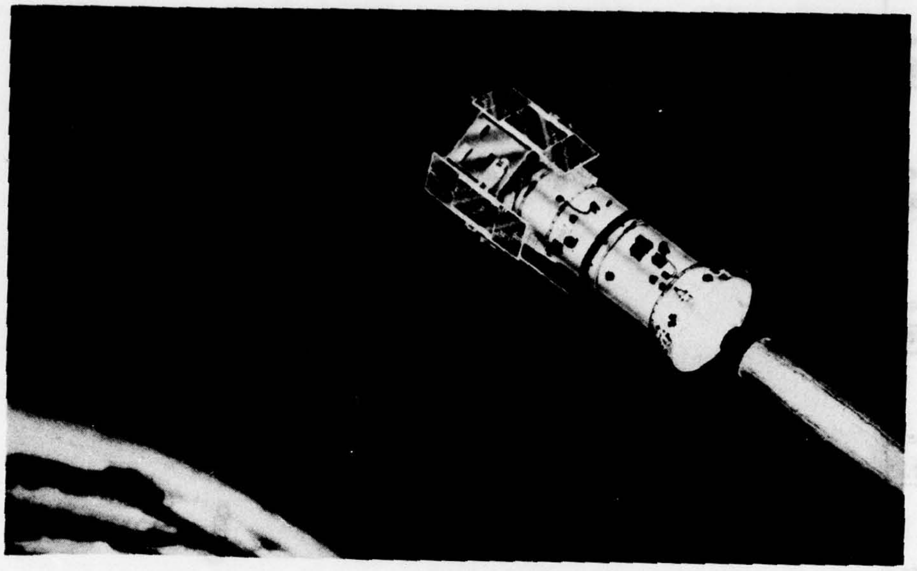

Fig. 1a - The NTS-2 satellite with solar paddles folded during launch

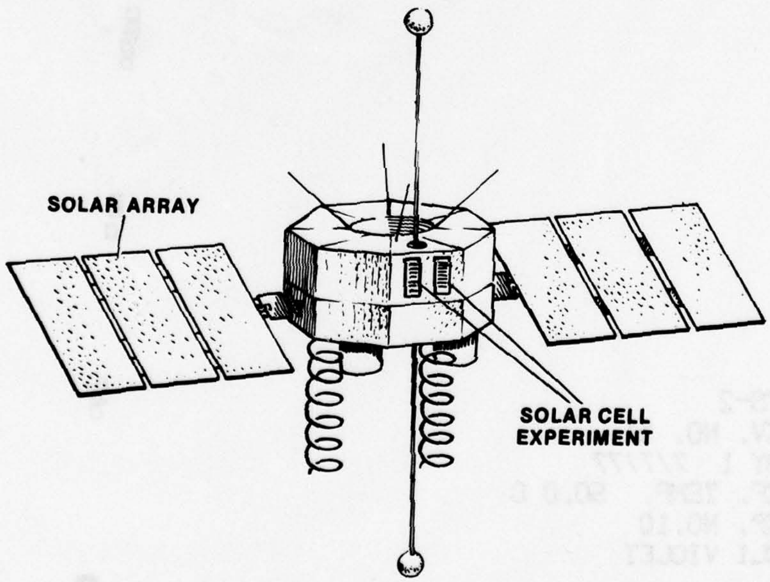

Fig. 1b - The NTS-2 satellite with solar arrays deployed and showing the location of the two solar cell experiment panels

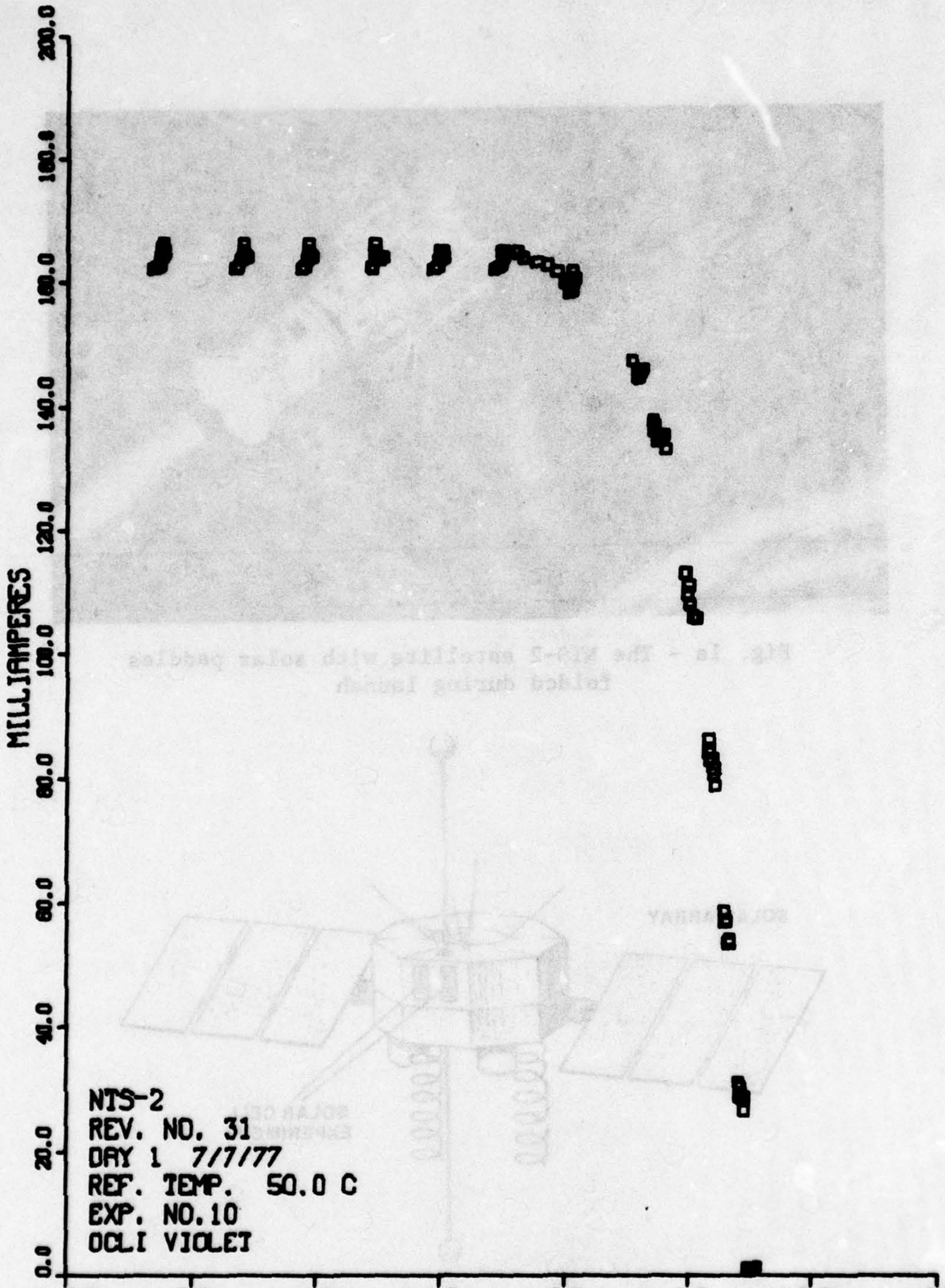

Figure 2. A typical current-voltage data curve as received from the NTS-2 satellite, corrected for solar intensity, sun angle and to a temperature of 50°C.

Temperatures are monitored at the rear surface of four cells by means of three thermistors and one wire resistance thermometer. The thermistors are accurate to within $\pm$ 3 degrees C up to 100 degrees C, and the wire thermometer is accurate to within $\pm$ 2 degrees C to above 120 degrees C. The experimental panels are continuously illuminated by the sun (except during the biannual eclipse season of 25 days) by virtue of the sun orientation requirements of the main array.

Since day 1, the panel temperatures have gradually increased to higher than 100 degrees C. The average temperatures of both solar cell panels versus days in orbit are shown in Figure 3. This temperature rise in excess of 20 degrees higher than predicted has been attributed to the ultraviolet and particle radiation degradation of the white silastic thermal control coating, DC 92007, that covers all panel areas surrounding the solar cell modules. The coated area totals 52 percent of the panels' surface. A closeup view of the panels is shown in Figure 4. It is proposed that exposure to ultraviolet and particle radiation has increased the α of the thermal control coating from 0.27 to about 0.45.

The first I_{sc} and V_{oc} data measured in space were in excellent agreement with the ground calibrations which were done at NRL and AFAPL. The data have been corrected for solar intensity (day of the year), for solar aspect angle and to a cell temperature of 50 degrees C.

Table 1 gives a brief description of the experiments, showing the type and thickness of the solar cell, the type and thickness of the coverslip, the

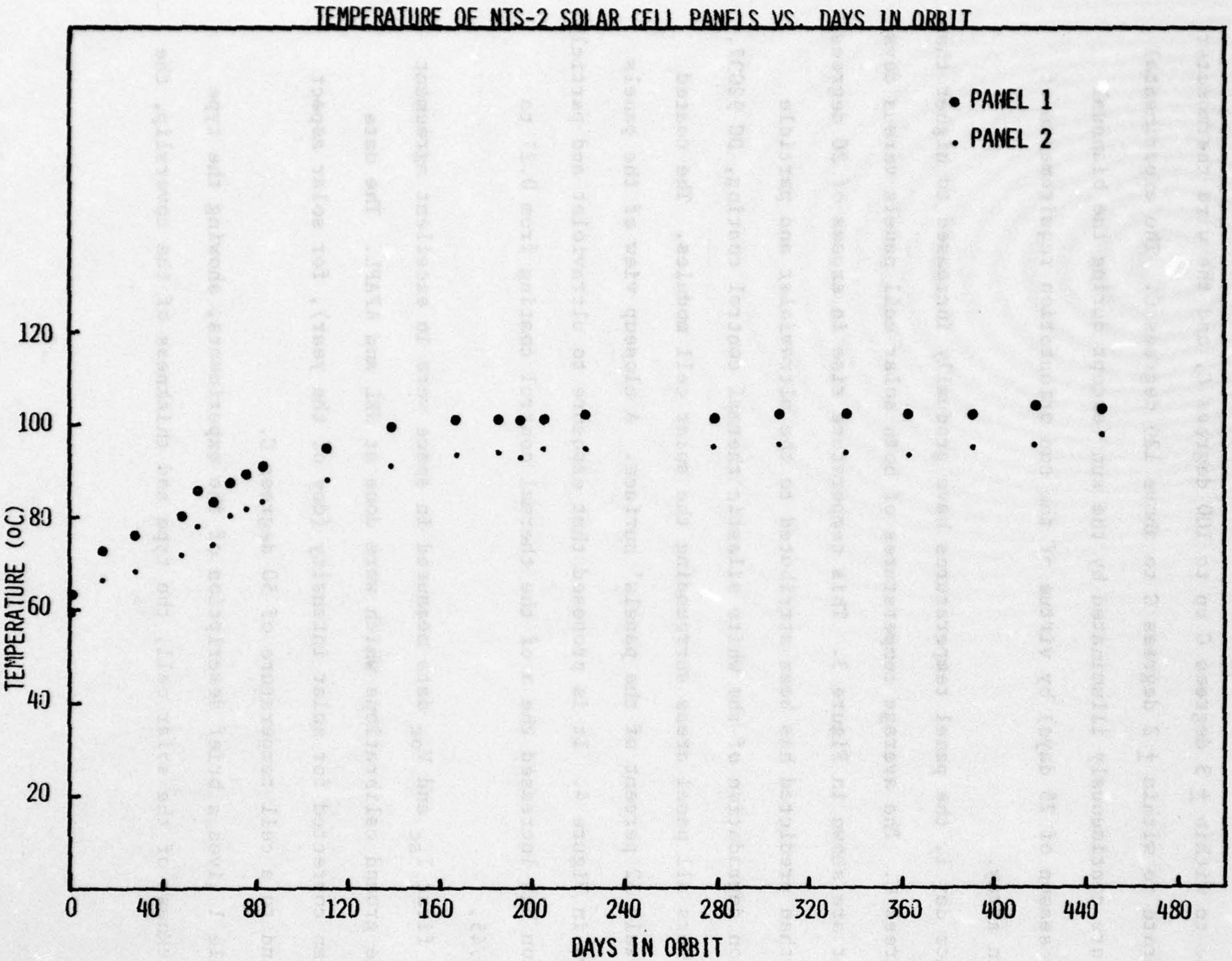

Figure 3. The average temperatures of the solar cell panels over the first 447 days in orbit.

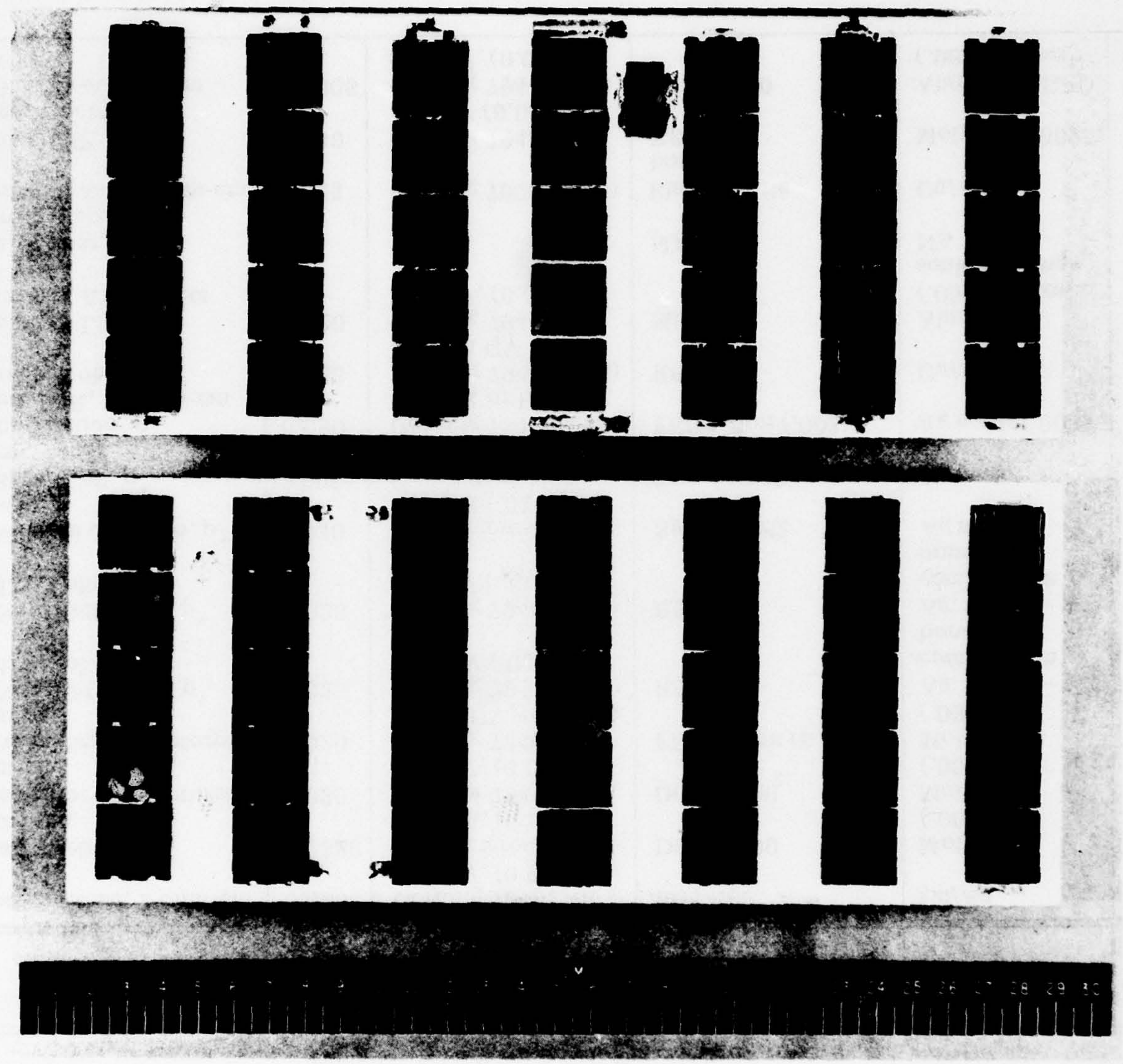

Figure 4. The NTS-2 solar cell experiment modules as mounted on the flight panels.

Table I — NTS-2 Solar Cell Experiments

Exp. No.	Cell Type	Thickness (cm)	Coverslip (cm)	Coverslip Bond (cm)	Interconnect	Efficiency 28°C (%)
1	OCLI Conventional, 2 ohm-cm	0.025	Corning 7940, AR and UV, (0.030)	R63-489	Cu/Ag	10.7
2	Spectrolab "Helios" p^+ 15-45 ohm-cm	0.0228	Ceria microsheet w/o AR, (0.025)	DC 93-500	Moly/Ag (.0025)	11.5
3	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, AR and UV, (0.0152)	DC 93-500	Moly/Ag (.0025)	10.5
4	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, w/o AR or UV, (0.0152)	FEP Teflon (0.0051)	Moly/Ag (.0025)	11.1
5	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR, w/o UV (.030)	R63-489	Ag; thermo-compression bonding	14.5
6	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR and UV (.030)	R63-489	Ag; thermo-compression bonding	14.6
7	Solarex Vertical Junction, p^+, 1.5 ohm-cm	0.030	Ceria microsheet w/o AR (.0152)	Sylgard 182	Ag mesh	13.0
8	Solarex Space Cell, p^+ 2 ohm-cm	0.025	Ceria microsheet w/o AR (0.0152)	Sylgard 182	Ag mesh	12.8
9	Spectrolab "Helios" p^+ Sculptured, BSR, 10 ohm-cm	0.030	Corning 7940 (.030) w/o AR or UV	FEP teflon (.003)	Ag mesh (.003)	14.2
10	OCLI Violet, 2 ohm-cm	0.025	Corning 7940 (.030) AR and UV	R63-489	Cu/Ag	13.5
11	Spectrolab P/N Li-doped 15-30 ohm-cm, Al contacts	0.020	Corning 7940, AR and UV, (0.015)	Silicone	Aluminum (.0025) Ultrasonic welding	10.8
12	Spectrolab Planar Diode in series with Exp. 11	NA	NA	NA	NA	NA
13	OCLI Conventional, 2 ohm-cm	0.025	Corning 7070 (.028)	Electrostatic bonding	Cu/Ag	10.2
14	Spectrolab HESP, no p^+, Sculptured, 2 ohm-cm	0.030	Corning 7940, AR and UV (0.0305)	R63-489	Moly/Ag (.0025)	13.6
15	Hughes Gallium-Aluminum Arsenide	0.0305	Corning 7940, AR and UV, (0.0305)	DC 93-500	Aluminum GPD (.0025), epoxy	13.6

nature of the coverslip to cell bonding, the interconnect material, and the beginning-of-life (BOL) cell efficiency.

The average spread in I_{sc} between NRL and AFAPL was only 2 mA; the average of these measurements is used as the ground calibration numbers reported here. The average error between I_{sc} on the first day in space and the pre-flight value is 1.41 $\pm$ 0.99 percent. The difference between V_{oc} in space and solar simulator values was 1.24 $\pm$ 1.08 percent. These are much more accurate results than were obtained for the NTS-1 solar cell experiment.[13] The NTS-1 experiment I_{sc} data deviated from the ground calibration by as much as 15 percent for some modules. There was an indication that this error was caused by a spurious voltage, such as a ground loop, in the data acquisition box.

The average error between P_m measurements on the ground and the first day in orbit was 3.33 $\pm$ 3.17 percent. The greatest difference was for the gallium arsenide cell, where the difference was 12.3 percent. This is not attributed entirely to measurement error, but it is believed there was a possibility for physical change in the cell module in the time between the last ground calibration with a solar simulator and the space measurement (145 days). The GaAs cell module showed a significant amount of P_M and V_{OC} recovery or "annealing" after 80 days in space (see Figure 5).

Three experiments have sustained unpredictably large degradations. The first of these, the Solarex "Low Cost Space Cell", Experiment 8, experienced an open-circuit of the module on the 69th day, causing the complete loss of subsequent data. Fortunately this failure occurred during a time while data were being recorded, allowing the abrupt manner in which it failed to be observed. The suddenness of the failure is shown in Figure 6.

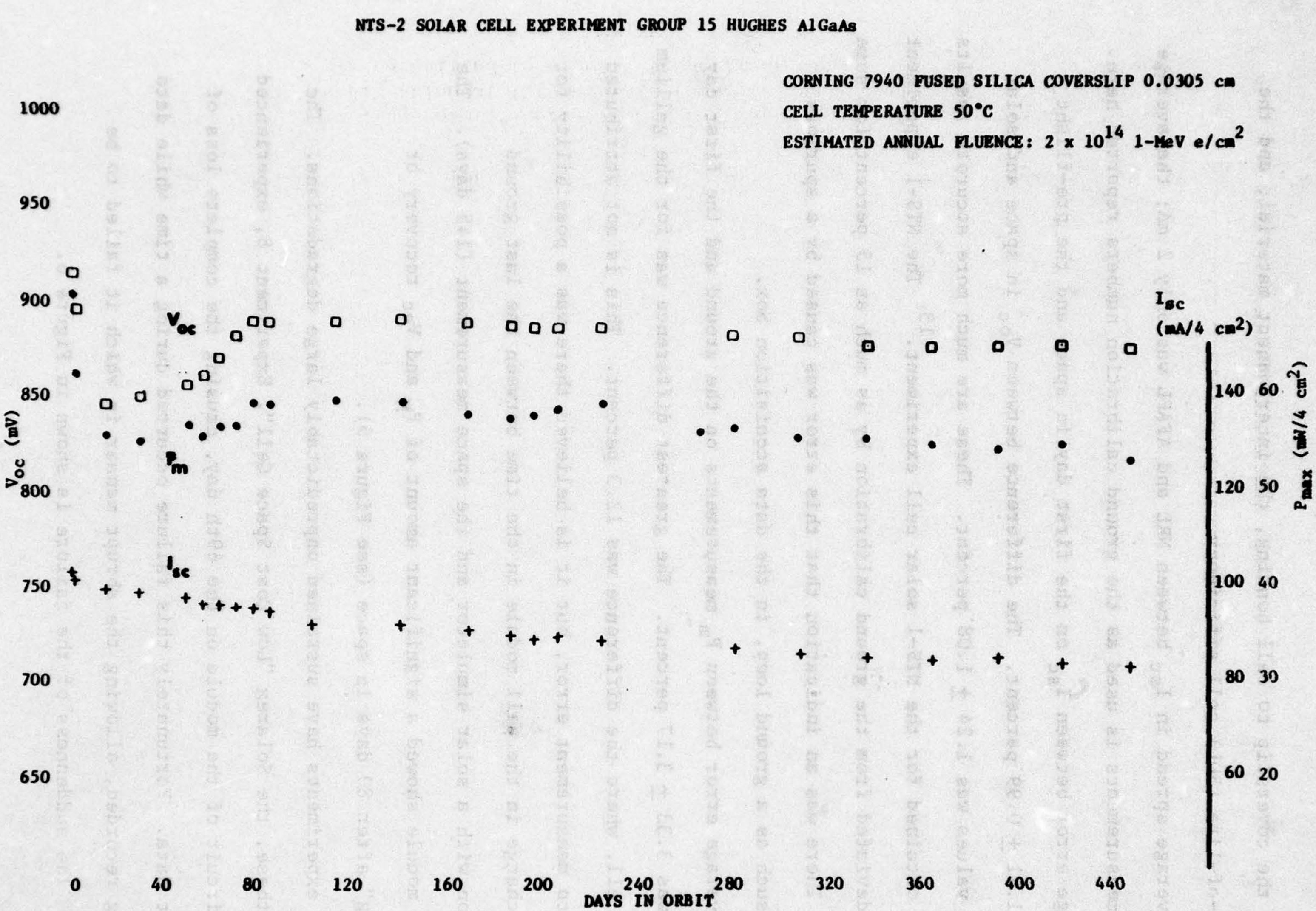

Figure 5. Maximum power, short-circuit current, and open-circuit voltage degradation of the Hughes gallium arsenide cell. P_{max} and I_{sc} are normalized to 4 cm^2. (Experiment 15)

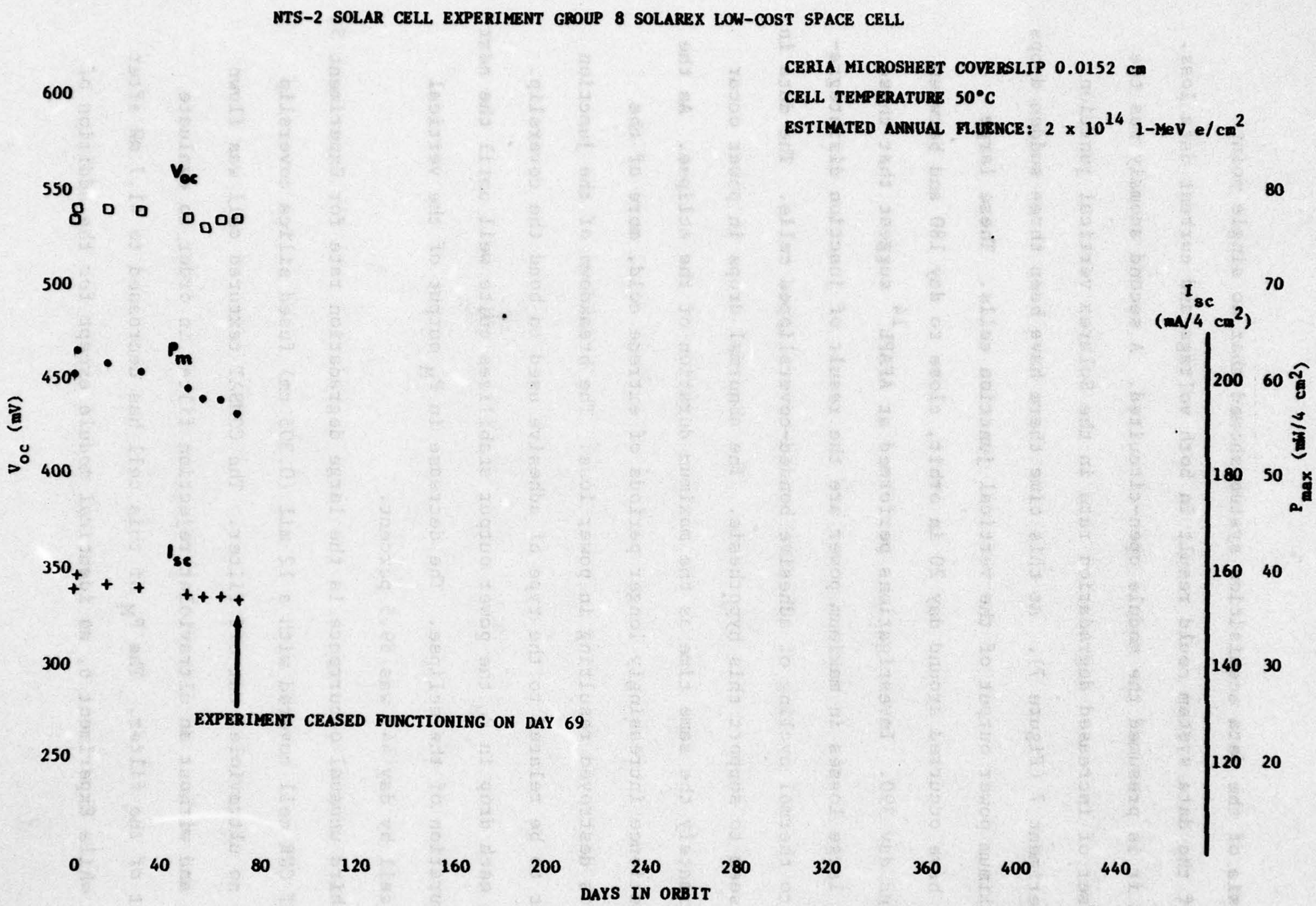

Figure 6. Maximum power, short-circuit current and open circuit voltage degradation of the Solarex "low-cost space cell". P_m and I_{sc} are normalized to 4 cm^2. (Experiment 8)

Analysis of the data acquisition system showed that no single point failure of the data system could result in both voltage and current data loss. Therefore it is presumed the module open-circuited. A second anomaly was the sudden onset of increased degradation rate in the Solarex vertical junction cell, Experiment 7 (Figure 7). At this time there have been three sudden drops in the maximum power output of the vertical junction cells. These large decreases have occurred around day 20 in orbit, close to day 180 and between day 365 and day 390. Investigations performed at AFAPL[14] suggest that these unusually large losses in maximum power are the result of junction disintegration due to thermal cycling of adhesive bonded-coverslipped cells. The data in Figure 7 seem to support this hypothesis. The abnormal drops in power occur at approximately the same time as the maximum duration of the eclipse. As the cells experience increasingly longer periods of extrene cold, more of the junction is destroyed resulting in power loss. The breakdown of the junction is thought to be related to the type of adhesive used to bond the coverslip. Following each drop in P_M the power output stabilizes quite well until the next maximum duration of the eclipse. The decrease in P_M output of the vertical junction cell by day 447 was 59.5 percent.

The third unusual occurrence is the large degradation rate for Experiment 5, the COMSAT CNR cell covered with a 12 mil (0.305 cm) fused silica coverslip which has no ultraviolet cut-off filter. The COMSAT textured cell was flown both with and without an ultraviolet rejection filter in order to evaluate the effect of the filter. The P_M of this cell has decreased to 41.7 mW after 447 days, while Experiment 6, an identical module except for the addition of

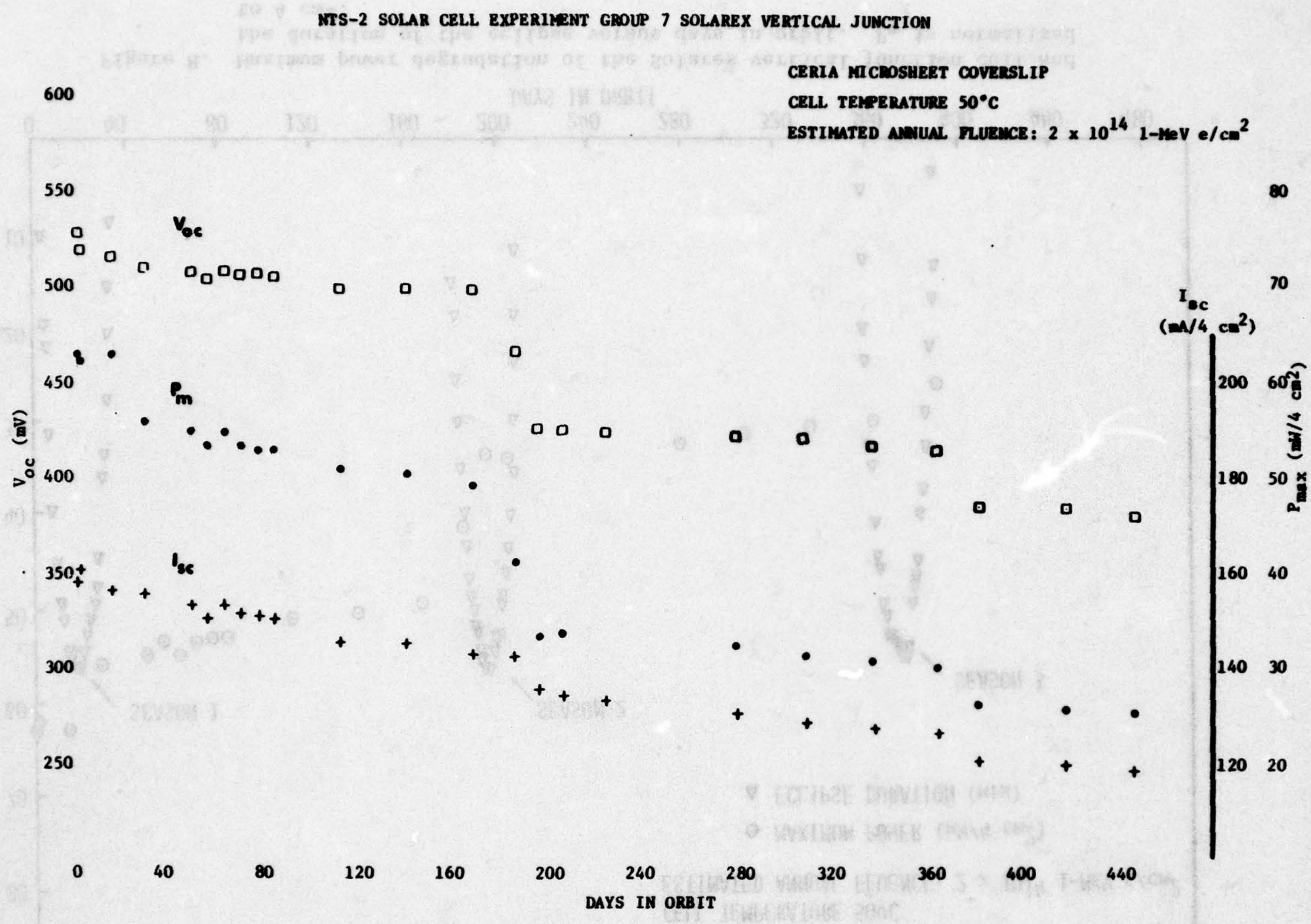

Figure 7. Degradation in maximum power, short-circuit current and open-circuit voltage of the Solarex vertical junction solar cell. P_m and I_{sc} are normalized to 4 cm^2. (Experiment 7)

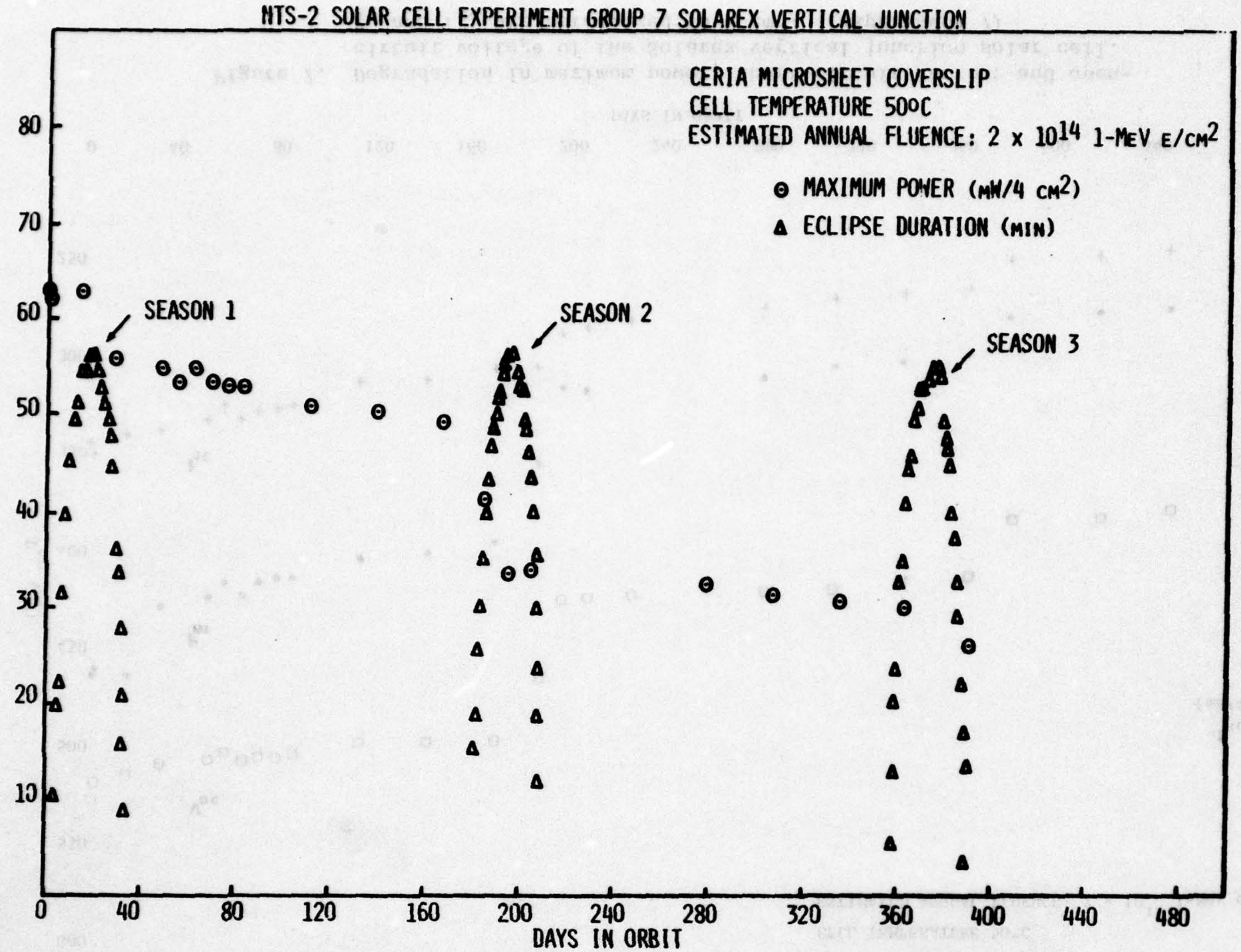

Figure 8. Maximum power degradation of the Solarex vertical junction cell and the duration of the eclipse versus days in orbit. P_m is normalized to 4 cm^2.

the ultraviolet cut-off filter on the coverslip, has a P_M of 56.8 mW. Although the two arrays start with approximately the same beginning-of-life short-circuit current, the I_{sc} of the cells with the uv filter (Experiment #6) degraded only 14.5 percent. However, the I_{sc} of Experiment #5 without the uv filter is down by 38.2 percent. Figure 9 shows the short-circuit current degradation of the COMSAT textured cell in both configurations. This amount is much greater than was expected solely from the absence of the uv filter. There may be another degradation factor involved which is so far unexplained. Most experiments indicate that degradation from ultraviolet degradation of the solar cell assembly is about 2 to 4 percent. The damage is thought to occur primarily during the first few days or weeks due to darkening of the adhesive. The coverslip adhesive is R63-489. There may be an unknown environmental factor or perhaps there is a defect in the adhesive layer in this case. Laboratory measurements at COMSAT Laboratories did not show a substantial difference with or without a filter.[15] If the degradation seen in the I_{sc} of these cells were caused by particle radiation in the cell, the V_{oc} would be severely degraded. Figure 10 shows that the V_{oc} of the cells with and without the uv filter is essentially the same. Neither the fill factor of Experiment #5 nor the knee of its I-V curve, which would be noticeably "softened", show any signs of radiation damage. We will continue to follow the behavior of these cells to determine the long-term effects of the absence of a uv filter. The flight data for Experiments 5 and 6 are shown in Figure 11 and Figure 12.

The remainder of the modules have operated as expected, although degrading more rapidly than predicted from the published reports.[16,17] Table 2 lists the P_M of the experiments at BOL and after 447 days in orbit.

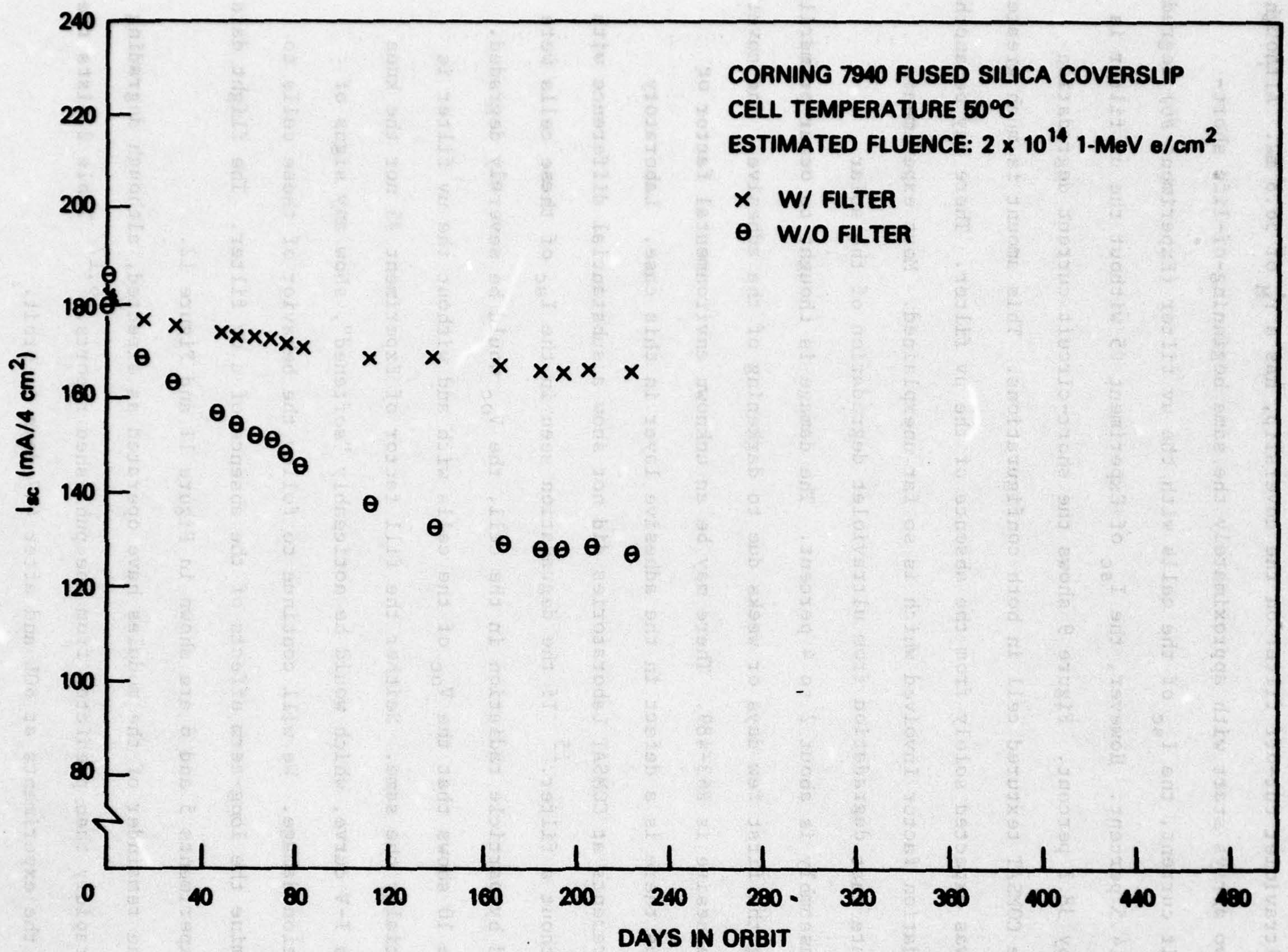

Figure 9. Short-circuit current degradation of the Comsat textured cell both with and without an ultraviolet rejection filter. Data are normalized to 4 cm^2.

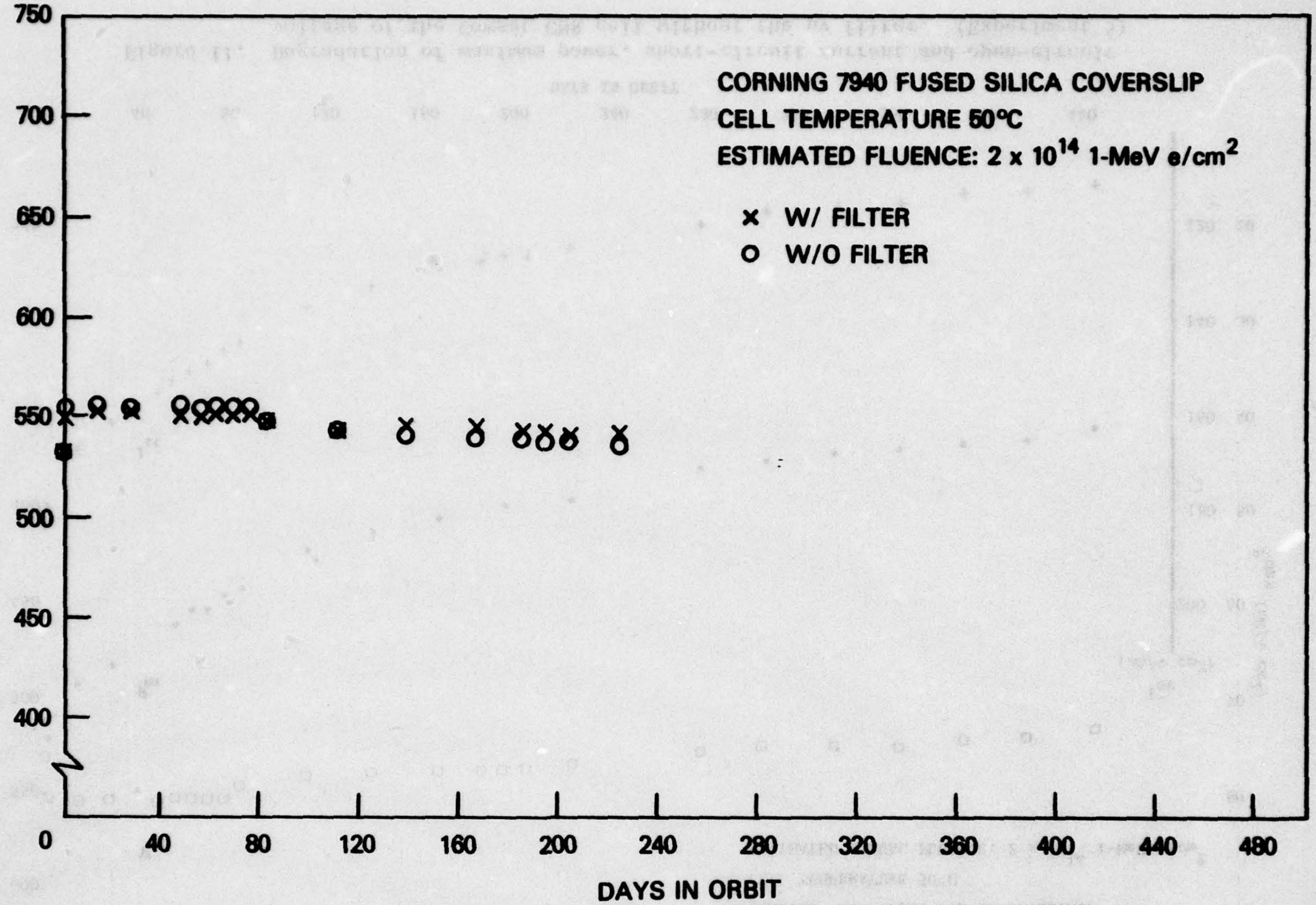

Figure 10. Open-circuit voltage degradation of the Comsat textured cell both with and without an ultraviolet rejection filter.

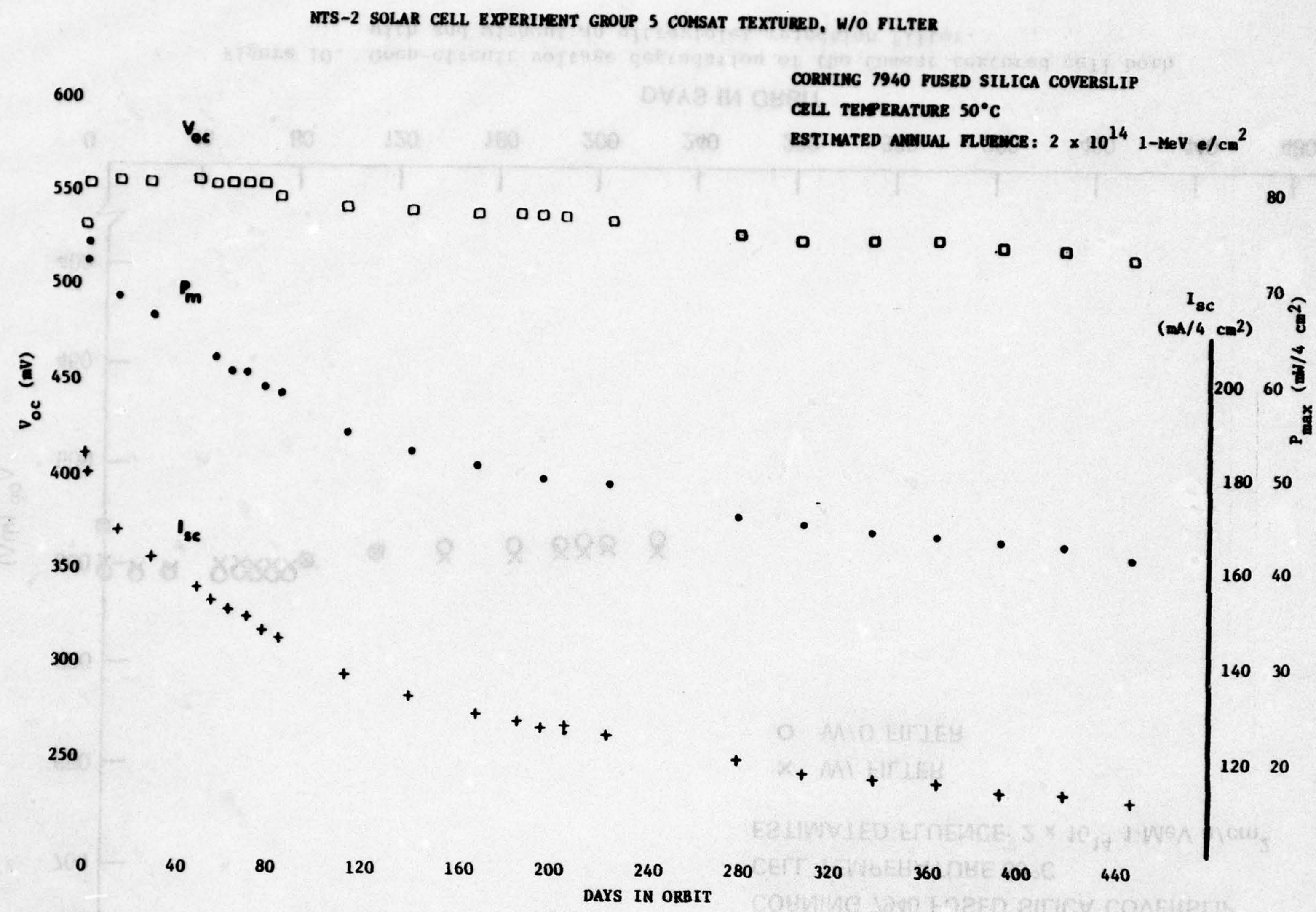

Figure 11. Degradation of maximum power, short-circuit current and open-circuit voltage of the Comsat CNR cell without the uv filter. (Experiment 5)

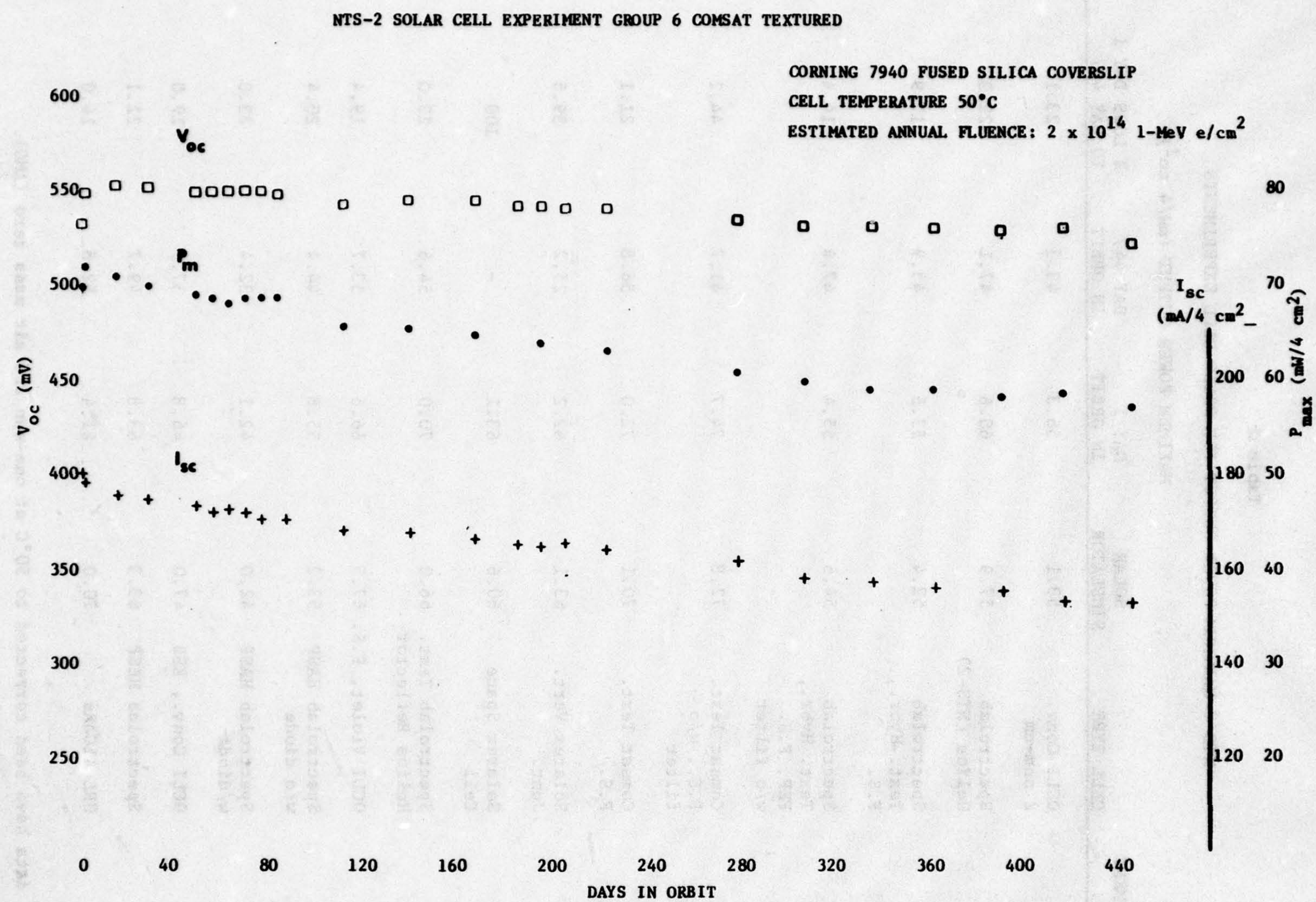

Figure 12. Degradation of maximum power, short-circuit current and open-circuit voltage of the Comsat CNR cell with an ultraviolet rejection filter. (Experiment 6)

Table 2

NTS-2 MAXIMUM POWER OUTPUT FOR SOLAR CELL EXPERIMENTS

EXPERIMENT NO.	CELL TYPE	SOLAR SIMULATOR	DAY 1 IN ORBIT	DAY 447 IN ORBIT	% LOSS DAY 1 TO DAY 447
		MAXIMUM POWER OUTPUT ($mW/4\ cm^2$)*			
1	OCLI Conv. 2 ohm-cm	53.1	56.3	43.3	23.1
2	Spectrolab Helios (NTS-2)	57.9	60.6	47.1	22.3
3	Spectrolab Text. Hybr., F.S.	52.4	53.5	43.9	17.9
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	54.6	55.4	47.4	14.4
5	Comsat Text. F.S., w/o filter	72.8	74.7	41.7	44.2
6	Comsat Text. F.S.	70.1	72.0	56.8	21.1
7	Solarex Vert. Junc.	63.1	62.2	25.2	59.5
8	Solarex Space Cell	60.6	63.1	-	100
9	Spectrolab Text. Helios Reflector	66.0	70.0	54.6	22.0
10	OCLI Violet, F.S.	67.5	66.6	53.7	19.4
11	Spectrolab HASP w/o diode	53.2	55.8	44.4	20.4
12	Spectrolab HASP w/diode	42.0	42.1	32.4	23.0
13	OCLI Conv., ESB	47.0	46.8	37.9	19.0
14	Spectrolab HESP	63.3	63.8	49.7	22.1
15	HRL AlGaAs	70.0	61.4	52.8	14.0

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

The solar cell experiments have been in orbit long enough to suffer sufficient radiation damage to allow one to make predictions of future damage rates. The fluence of equivalent 1-MeV electrons/cm^2 experienced by four (4) selected groups of solar cells (Experiment 1, the OCLI conventional cell; Experiment 2, the Spectrolab Helios cell; Experiment 3, the Spectrolab textured hybrid cell and Experiment 10, the OCLI violet cell) by day 200 is tabulated in Table 3. The corrected space data for these experiments are shown in Figures 13-16. These data were used to predict the estimated annual fluence and the fluence expected over 3 years. The OCLI 2 ohm-cm cell is used as a reference because the effects of varied amounts of fluence on these cells have been studied extensively. The Spectrolab Helios cell is being considered for the power system for NTS-3. The Spectrolab hybrid cell and the OCLI violet cell are also being studied as possible choices. The predicted degradation rate of P_M calculated from these experiments for the first three years in orbit is plotted in Figure 17 along with the experimental data. The space data indicates a slightly harder radiation environment.

The relative degradations of the cells mentioned above, as calculated for day 200, and predicted for 1 year and 3 years, are shown in Table 4. On day 447 the P_M of each of the experiments was approximately 2 percent lower than predicted. The degradation curves for these three modules, Experiments 1, 2, and 10 in Figure 18 were compared with laboratory results of 1-MeV electron irradiation tests of similar cells. From these data we obtained values for DENI space fluence of 1.6-2.7 x 10^{14} 1-MeV electron/cm^2·year. These estimates are being used in the design of the Navigation Technology Satellite III (NTS-3)

Table III — NTS-2 Equivalent Fluence (1 - MeV e/cm²) Predictions*

	BOL	Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
OCLI Conventional 2 Ω-cm, 10 mil cell, 12 mil FS Coverslip				
I_{sc}	136.0 mA	1.5×10^{14}	2.7×10^{14}	8.2×10^{14}
V_{oc}	548 mV	3×10^{13}	5.5×10^{13}	1.6×10^{14}
P_m	56.5 mW/4 cm²	1.3×10^{14}	2.4×10^{14}	7.1×10^{14}
Spectrolab Helios, 10 Ω-cm, 9 mil cell, 10 mil Ceria Coverslip				
I_{sc}	154 mA	1.3×10^{14}	2.4×10^{14}	7.1×10^{14}
V_{oc}	545 mV	1×10^{13}	1.8×10^{13}	5.5×10^{13}
P_m	60.5 mW/4 cm²	9×10^{13}	1.6×10^{14}	4.9×10^{14}
Spectrolab Textured Hybrid, 8 mil cell, 6 mil FS Coverslip				
I_{sc}	156 mA	5.0×10^{14}	9.1×10^{14}	2.7×10^{15}
V_{oc}	522 mV	5.0×10^{14}	9.1×10^{14}	2.7×10^{15}
P_m	53.8 mW/4 cm²	3.3×10^{14}	6.0×10^{14}	1.8×10^{15}
OCLI Violet				
I_{sc}	166 mA	1×10^{13}	1.8×10^{14}	5.5×10^{14}
V_{oc}	552 mV	2×10^{13}	3.7×10^{13}	1.1×10^{14}
P_m	67.5 mW/4 cm²	7.5×10^{13}	1.4×10^{14}	4.1×10^{14}

*Cell data at 50°C

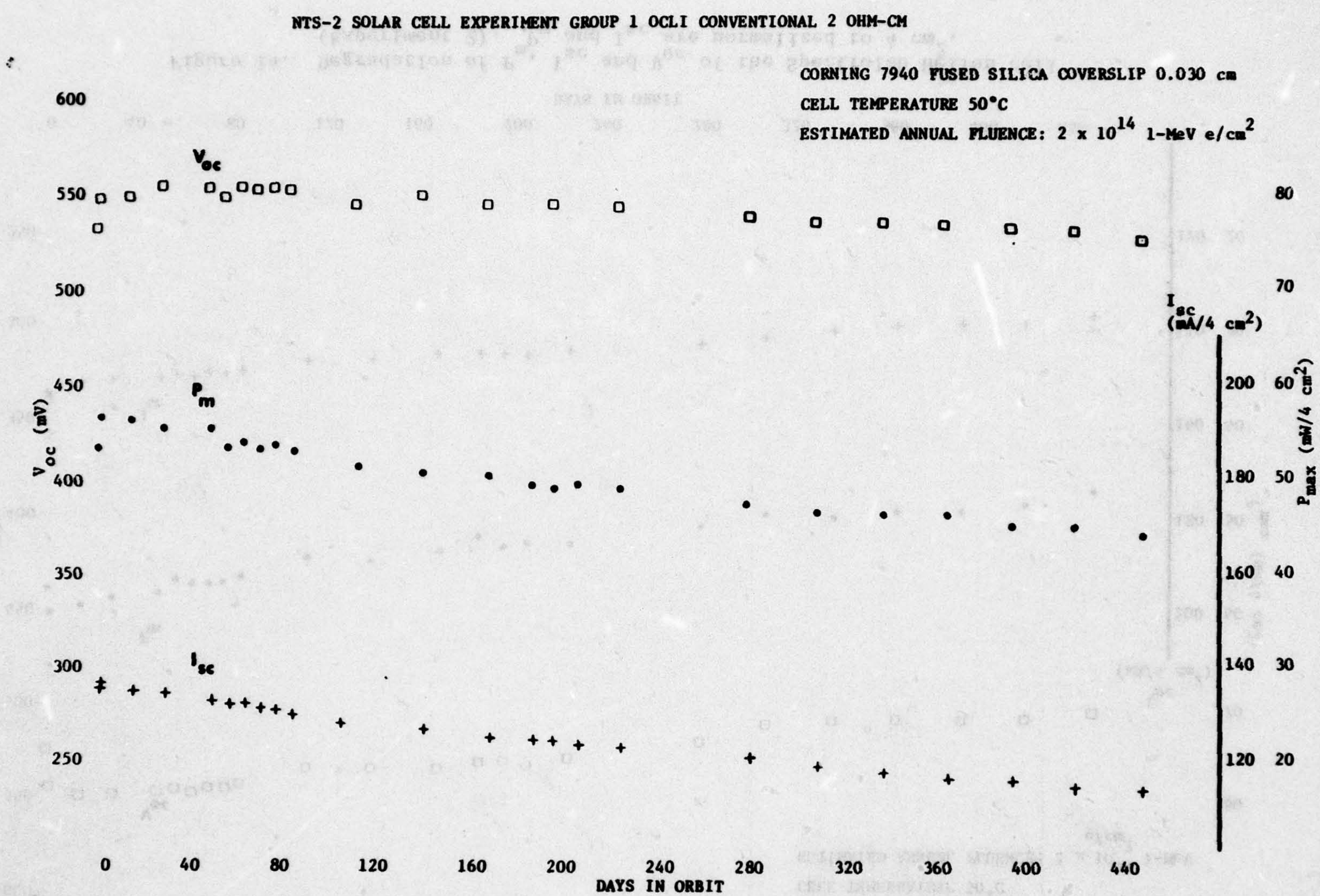

Figure 13. Degradation of maximum power, short-circuit current and open-circuit voltage of the OCLI conventional solar cell. (Experiment 1) P_m and I_{sc} are normalized to 4 cm^2.

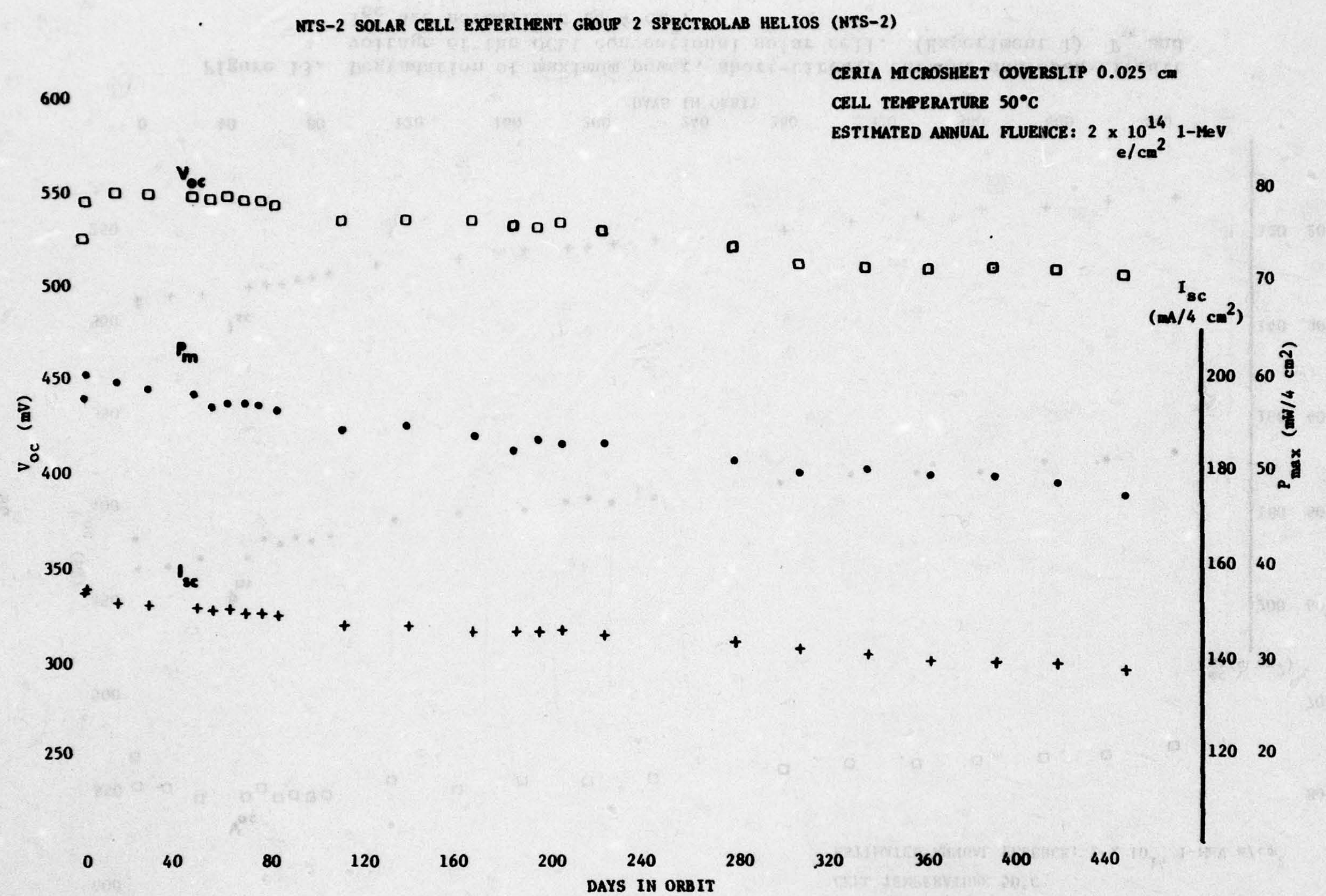

Figure 14. Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab Helios cell (Experiment 2). P_m and I_{sc} are normalized to 4 cm^2.

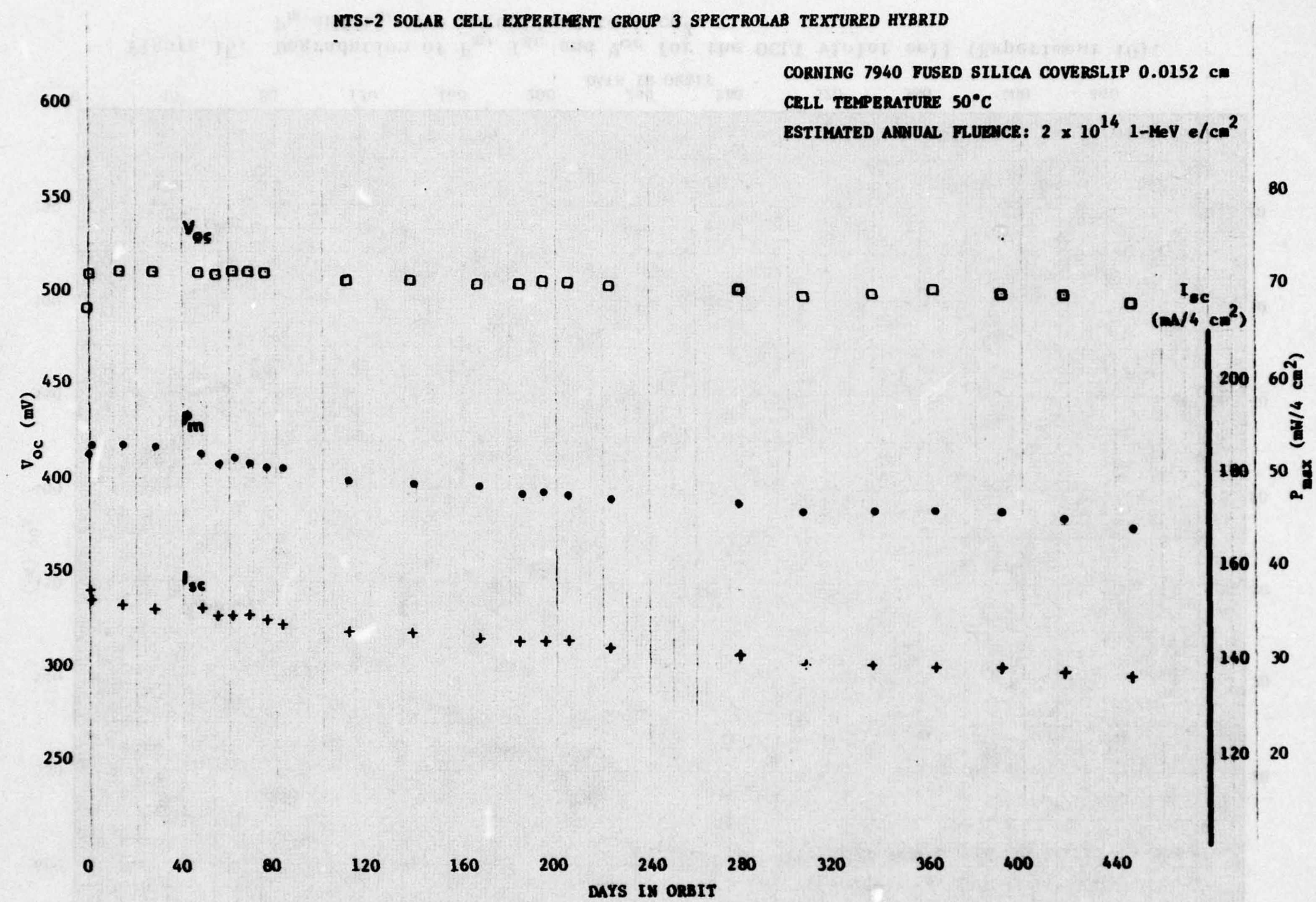

Figure 15. Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab textured hybrid cell (Experiment 3). P_m and I_{sc} are normalized to 4 cm^2.

NTS-2 SOLAR CELL EXPERIMENT GROUP 10 OCLI VIOLET

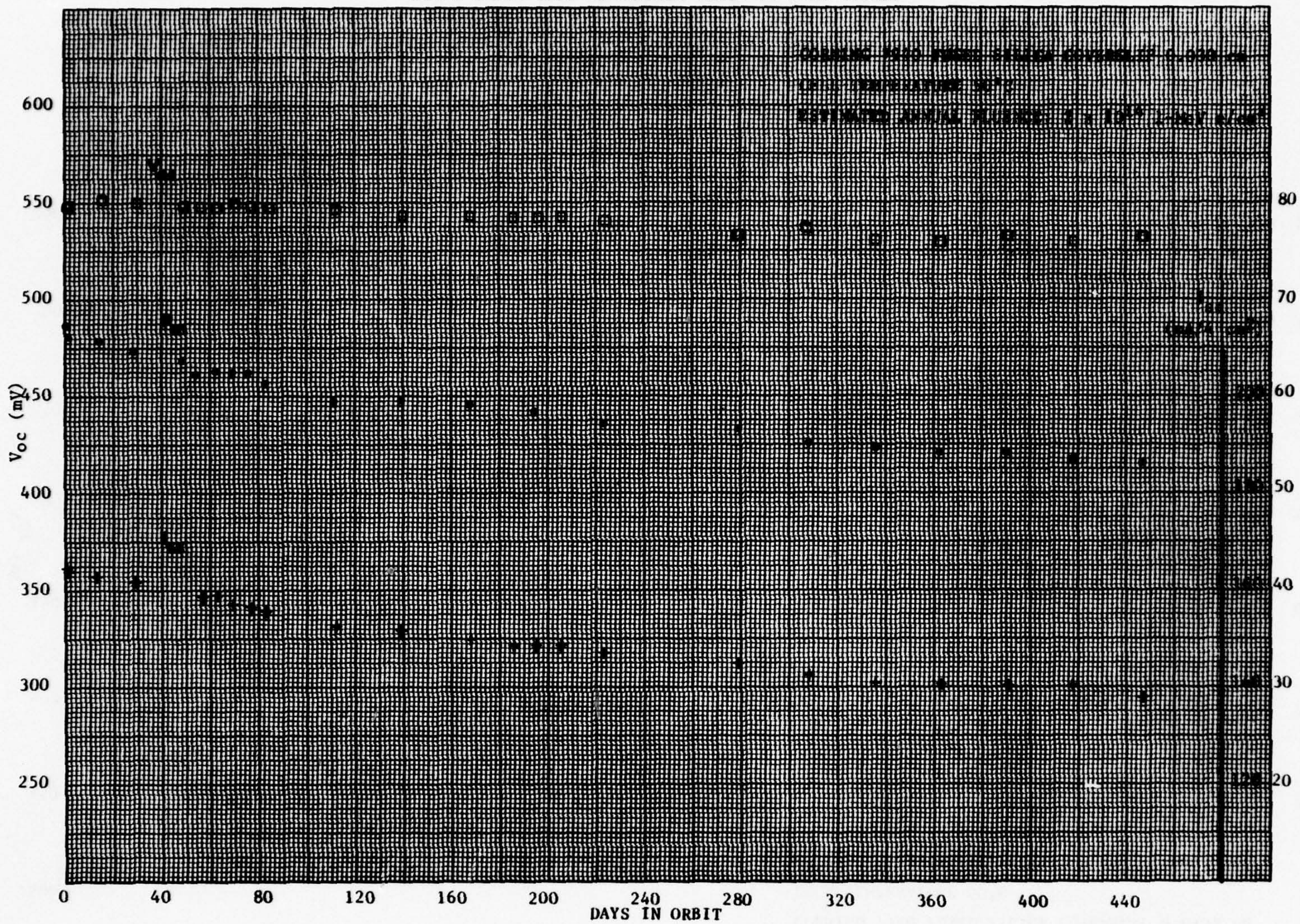

Figure 16. Degradation of P_m, I_{sc} and V_{oc} for the OCLI violet cell (Experiment 10). P_m and I_{sc} are normalized to 4 cm^2.

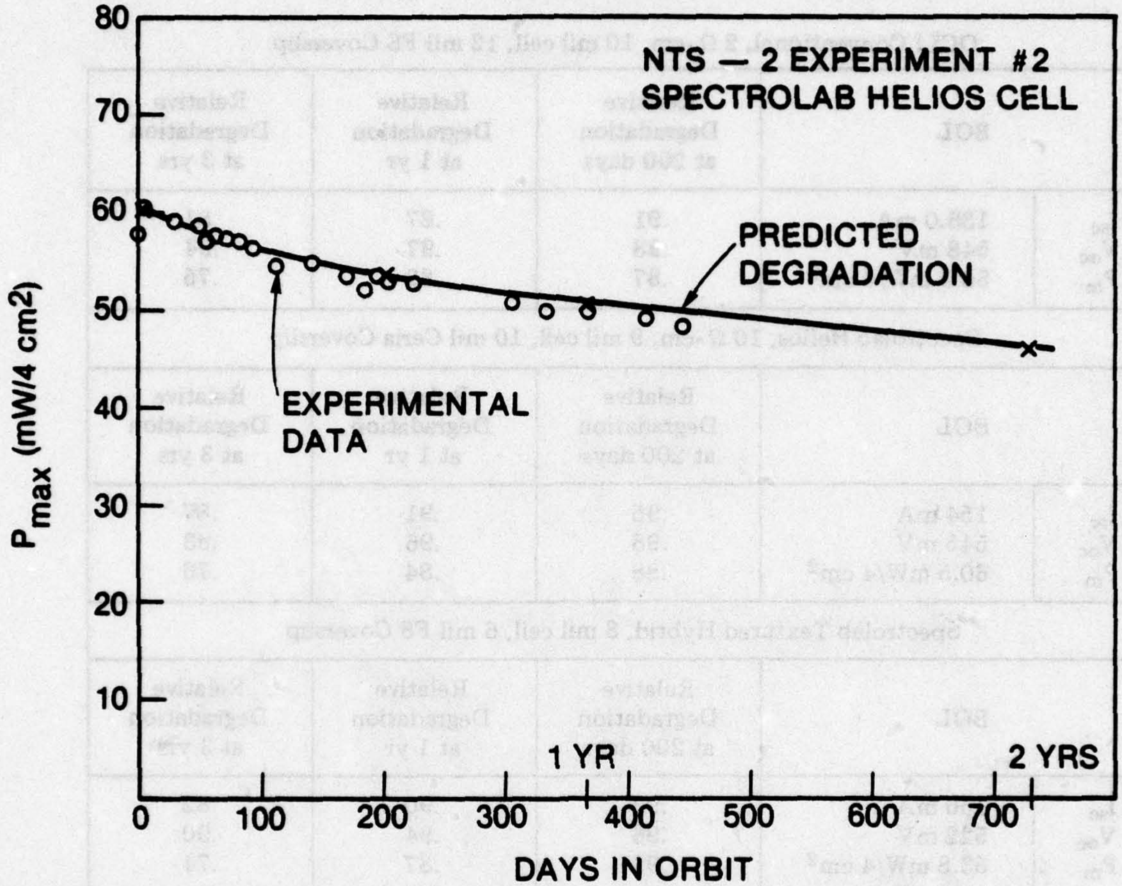

Figure 17. Predicted degradation rate for the Spectrolab Helios cell over a three-year period.

Table IV — Percent of I_{sc}, V_{oc} and P_{max} Remaining after 200 Days in Orbit and Predictions for Percent Remaining at 1 yr and 3 yrs*

	BOL	Relative Degradation at 200 days	Relative Degradation at 1 yr	Relative Degradation at 3 yrs
OCLI Conventional, 2 Ω-cm, 10 mil cell, 12 mil FS Coverslip				
I_{sc}	136.0 mA	.91	.87	.81
V_{oc}	548 mV	.98	.97	.94
P_m	56.5 mW/4 cm^2	.87	.82	.75
Spectrolab Helios, 10 Ω-cm, 9 mil cell, 10 mil Ceria Coverslip				
I_{sc}	154 mA	.95	.91	.87
V_{oc}	545 mV	.98	.96	.93
P_m	60.5 mW/4 cm^2	.88	.84	.76
Spectrolab Textured Hybrid, 8 mil cell, 6 mil FS Coverslip				
I_{sc}	156 mA	.93	.90	.82
V_{oc}	522 mV	.96	.94	.90
P_m	53.8 mW/4 cm^2	.90	.87	.74
OCLI Violet, 10 mil cell, 12 mil FS Coverslip				
I_{sc}	166 mA	.90	.84	.80
V_{oc}	552 mV	.98	.97	.95
P_m	67.5 mW/4 cm^2	.87	.83	.75

*Cell data at 50°C

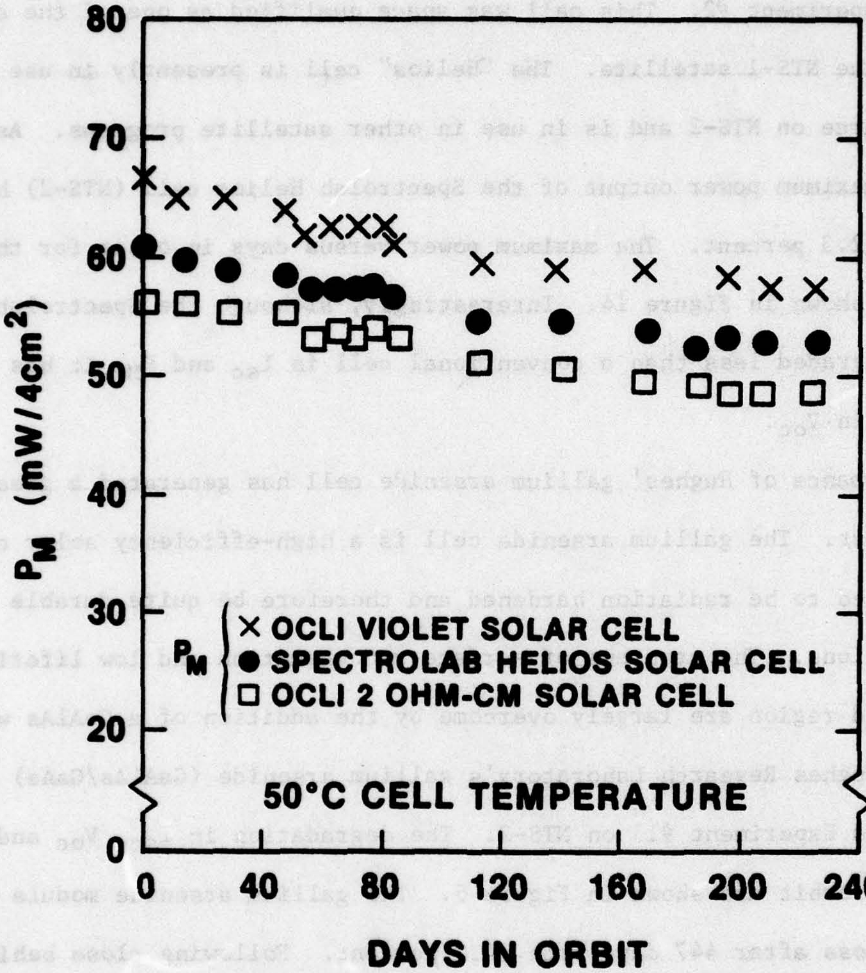

Figure 18. Comparison of power degradation in the OCLI violet, Spectrolab Helios and the OCLI conventional solar cells.

at NRL. The launch date is scheduled for October 1981, at a time also of increased solar proton activity.

Among the experiments of primary interest is the Spectrolab "Helios" back field cell, Experiment #2. This cell was space qualified as one of the experiments aboard the NTS-1 satellite. The "Helios" cell is presently in use as the main power source on NTS-2 and is in use in other satellite programs. As of day 447, the maximum power output of the Spectrolab Helios cell (NTS-2) has decreased by 22.3 percent. The maximum power versus days in orbit for this experiment is shown in Figure 14. Interestingly, although the Spectrolab Helios cell degraded less than a conventional cell in I_{sc} and P_M, it has degraded more in V_{oc}.

The performance of Hughes' gallium arsenide cell has generated a great deal of interest. The gallium arsenide cell is a high-efficiency solar cell that is expected to be radiation hardened and therefore be quite durable for space applications. The problems of surface recombination and low lifetime in the diffused region are largely overcome by the addition of a GaAlAs window. The array of Hughes Research Laboratory's gallium arsenide (GaAlAs/GaAs) solar cells comprises Experiment #15 on NTS-2. The degradation in I_{sc}, V_{oc} and P_M versus days in orbit are shown in Figure 5. The gallium arsenide module shows the least P_M loss after 447 days with 14.0 percent. Following close behind is Experiment #4, the textured hybrid cell with FEP bonded coverslip down 14.4 percent.

Experiments 3 and 4 were designed to distinguish between cell degradation effects due to adhesive bonding vs. FEP Teflon bonding. There is a decided

improvement for the Teflon bonded coverslip (14.4 percent degradation) using "as sawn fused silica" instead of the traditional polished and uv filtered Corning 7940 fused silica (degradation in P_M 17.9 percent). These data are presented in Figures 15 and 19.

Another coverslip evaluation is made in Experiments 1 and 13 which use an OCLI conventional cell, Experiment 1 with an adhesive bonded Corning 7940 fused silica coverslip and Experiment 13 with an electrostatic bonded Corning 7070 glass coverslip. There is a slight loss in BOL P_M with the electrostatic bonding technique. The percentage power loss after 447 days in orbit is slightly less for the ESB cell at 19.0 percent compared to the 23.1 percent P_M loss in the adhesive bonded cell. These results are shown in Figures 13 and 20.

Experiments 11 and 12 were designed to evaluate the behavior of a diode in series with solar cells in the space radiation environment. The data from Experiment 11 and Experiment 12 are shown in Figures 21 and 22 respectively. As shown in Figure 23, the voltage drop across the diode has not changed significantly over the 447 days in space.

The Spectrolab textured Helios reflector, Experiment 9, and the Spectrolab HESP cells, Experiment 14, have degraded in P_M 22.0 percent and 22.1 percent respectively. Experiment 9 is shown in Figure 24 and Experiment 14 is shown in Figure 25.

The absolute and percent changes of short-circuit current and open-circuit voltage are listed in Tables 5 and 6. The percent changes in I_{sc}, V_{OC} and P_M are summarized in Table 7.

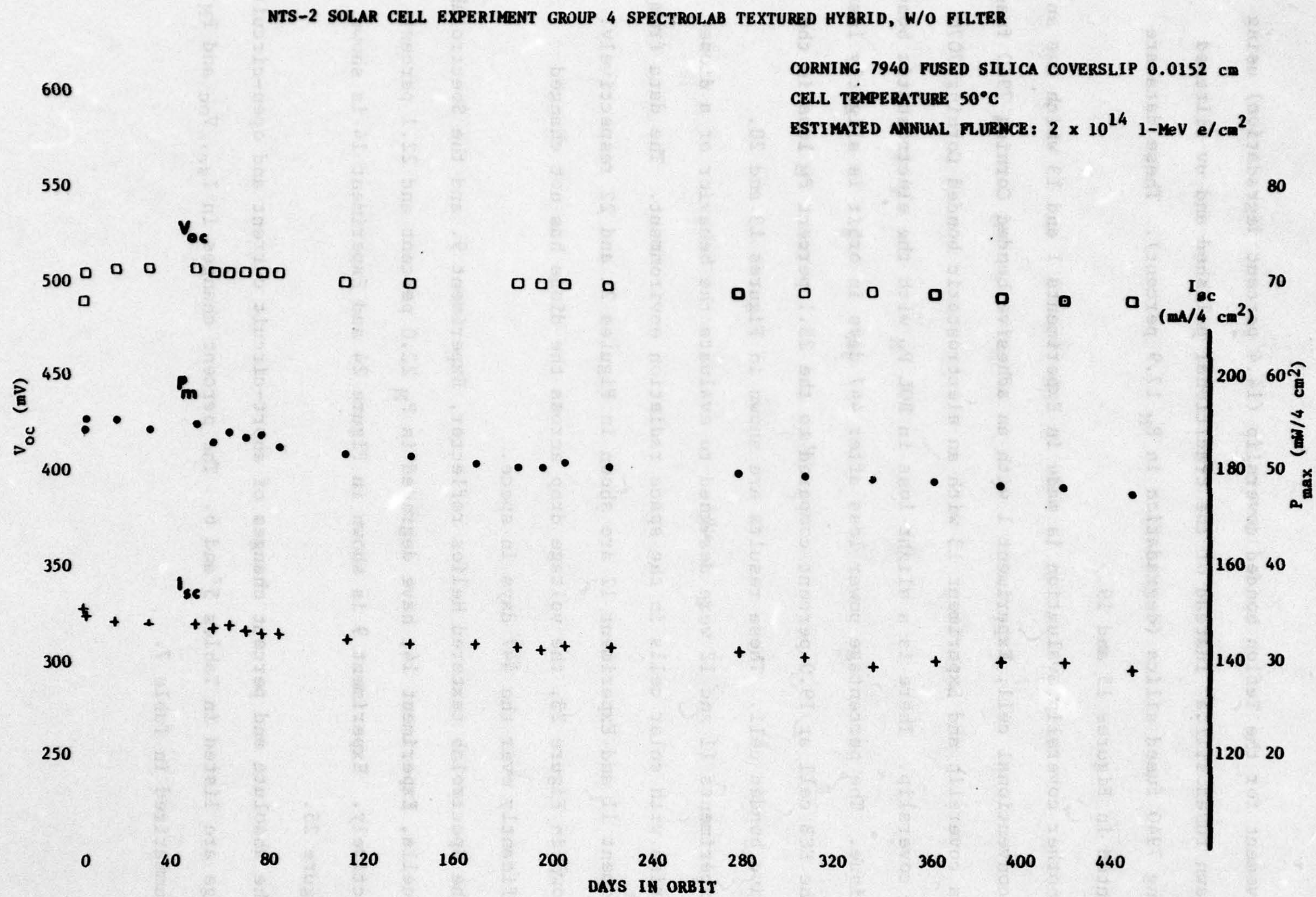

Figure 19. Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab textured hybrid solar cell with FEP Teflon bonded coverslip (Experiment 4). P_m and I_{sc} are normalized to 4 cm^2.

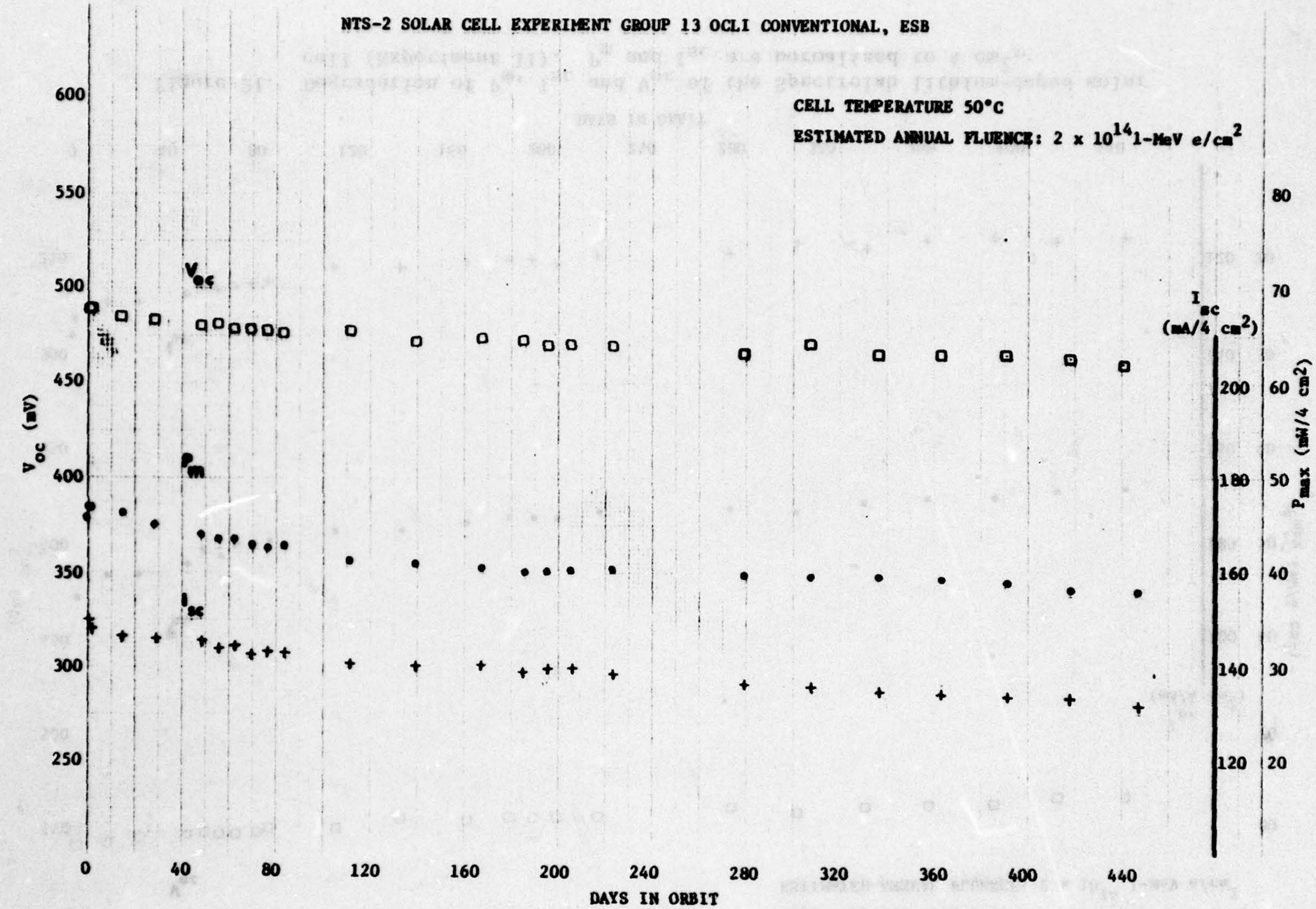

Figure 20. Degradation of P_m, I_{sc} and V_{oc} of the OCLI conventional solar cell with electrostatically bonded coverslip (Experiment 13). P_m and I_{sc} are normalized to 4 cm^2.

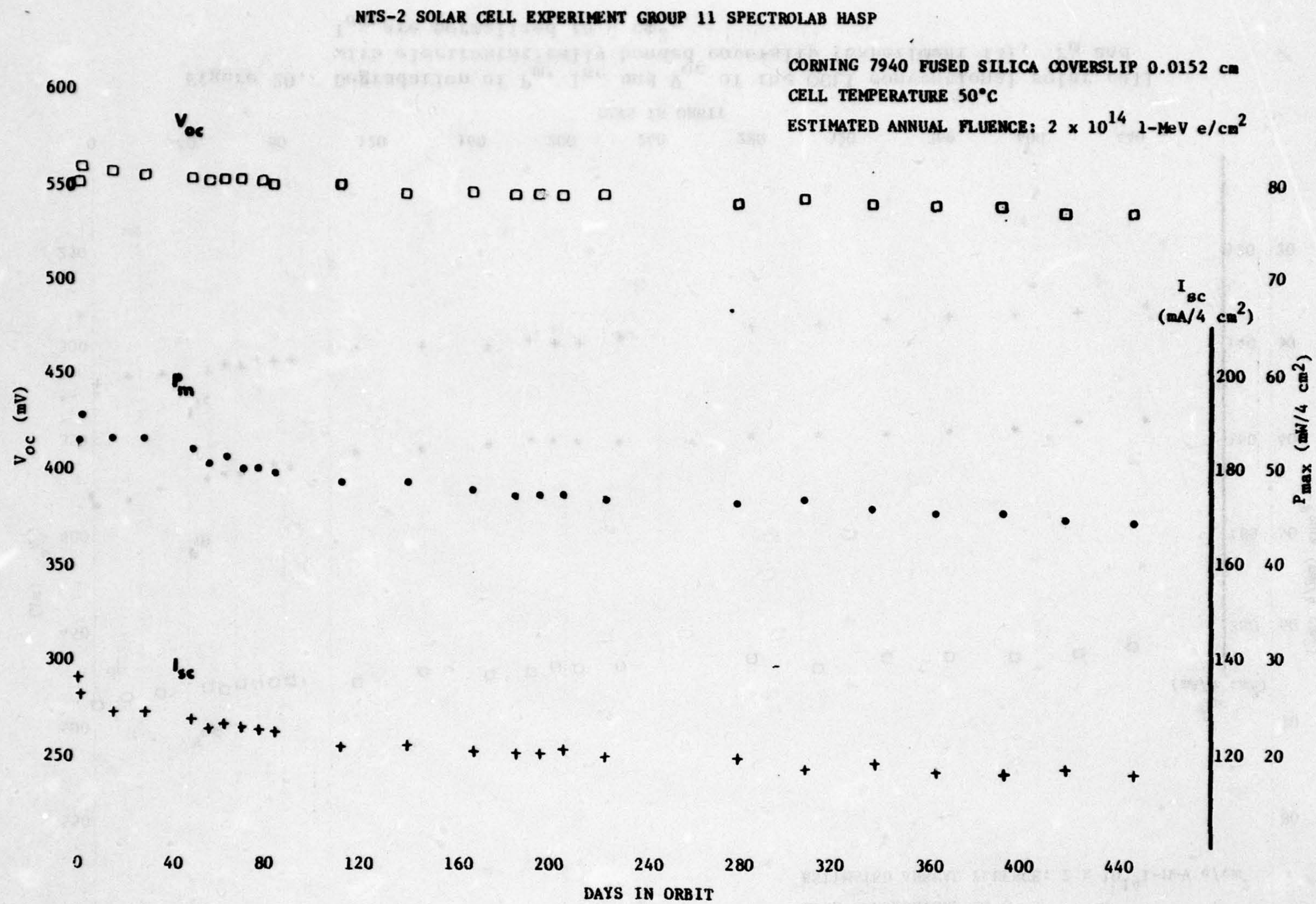

Figure 21. Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab lithium-doped solar cell (Experiment 11). P_m and I_{sc} are normalized to 4 cm^2.

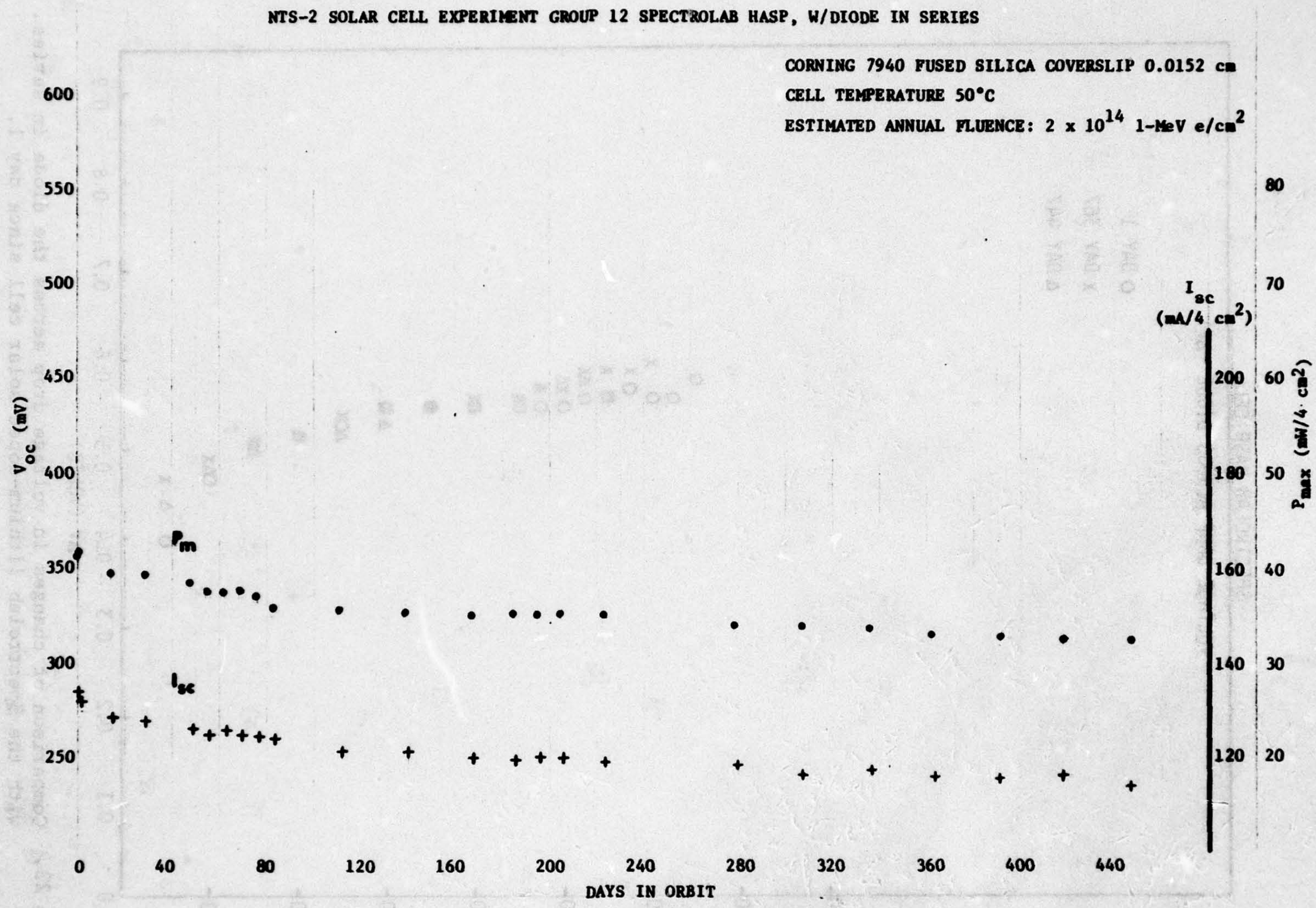

Figure 22. Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab lithium-doped solar cell in series with a planar diode.

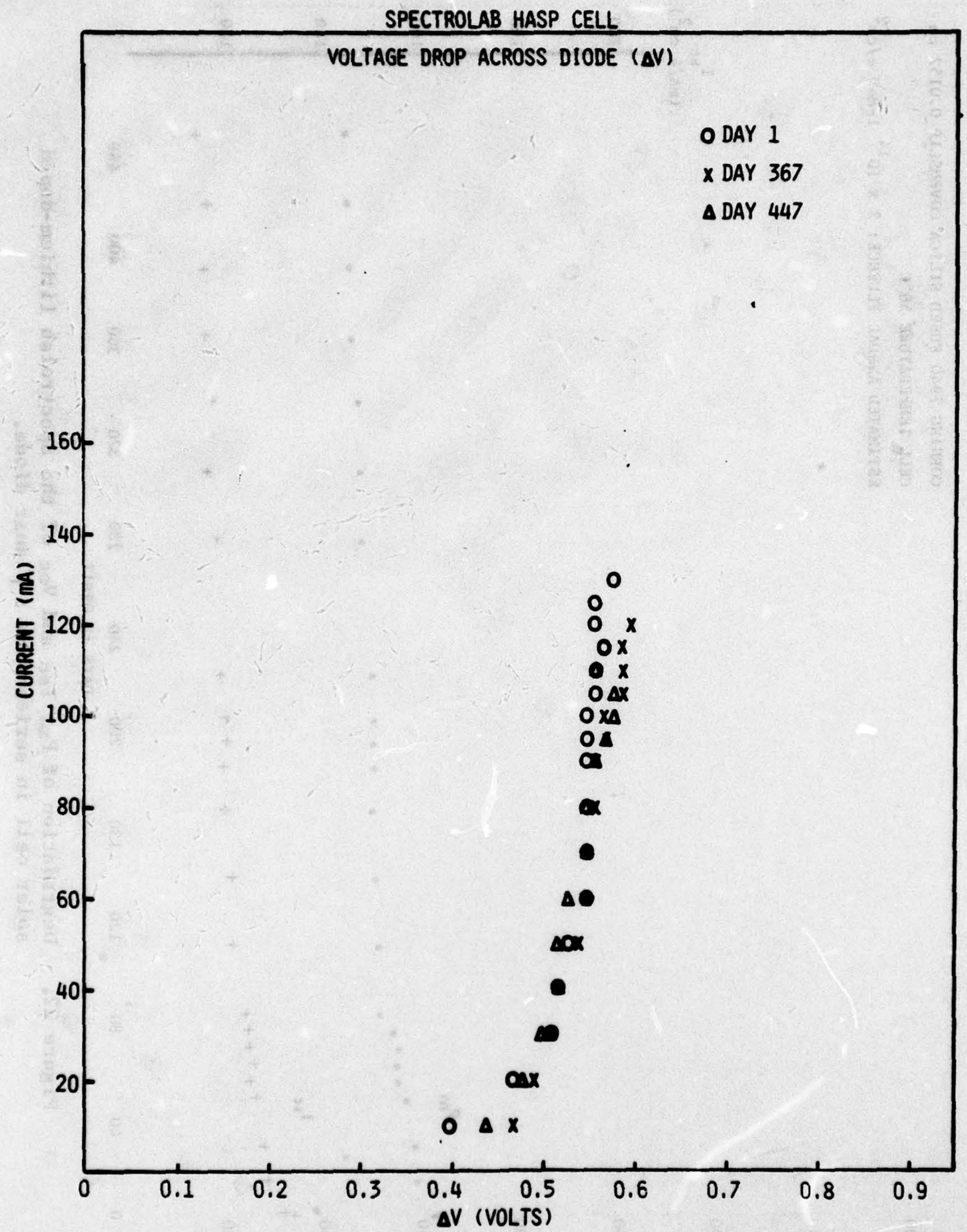

Figure 23. Comparison of changes in voltage drop across the diode in series with the Spectrolab lithium-doped solar cell since day 1.

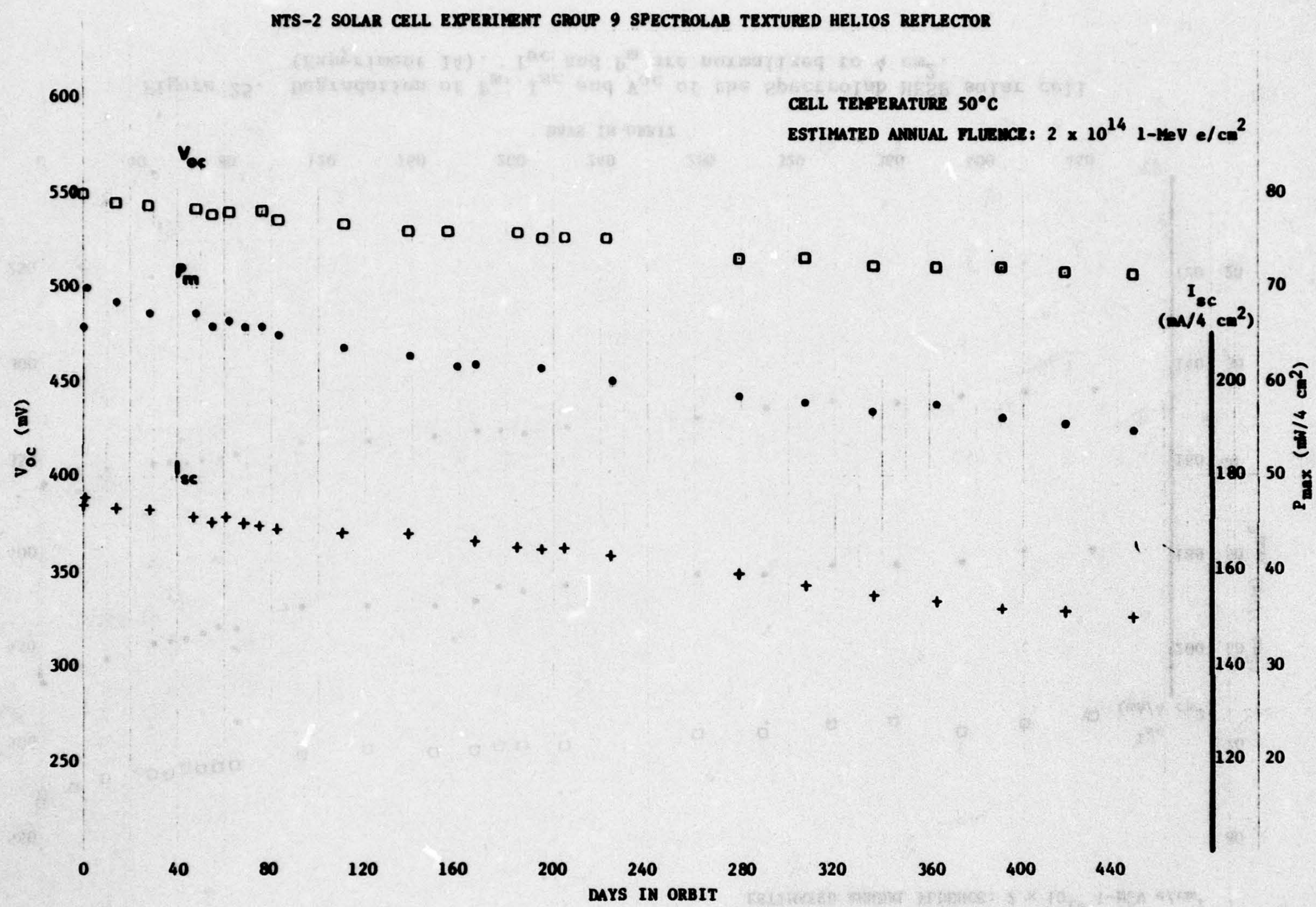

Figure 24. Degradation of P_m, V_{oc} and I_{sc} of the Spectrolab Helios reflector cells (Experiment 9). P_m and I_{sc} are normalized to 4 cm^2.

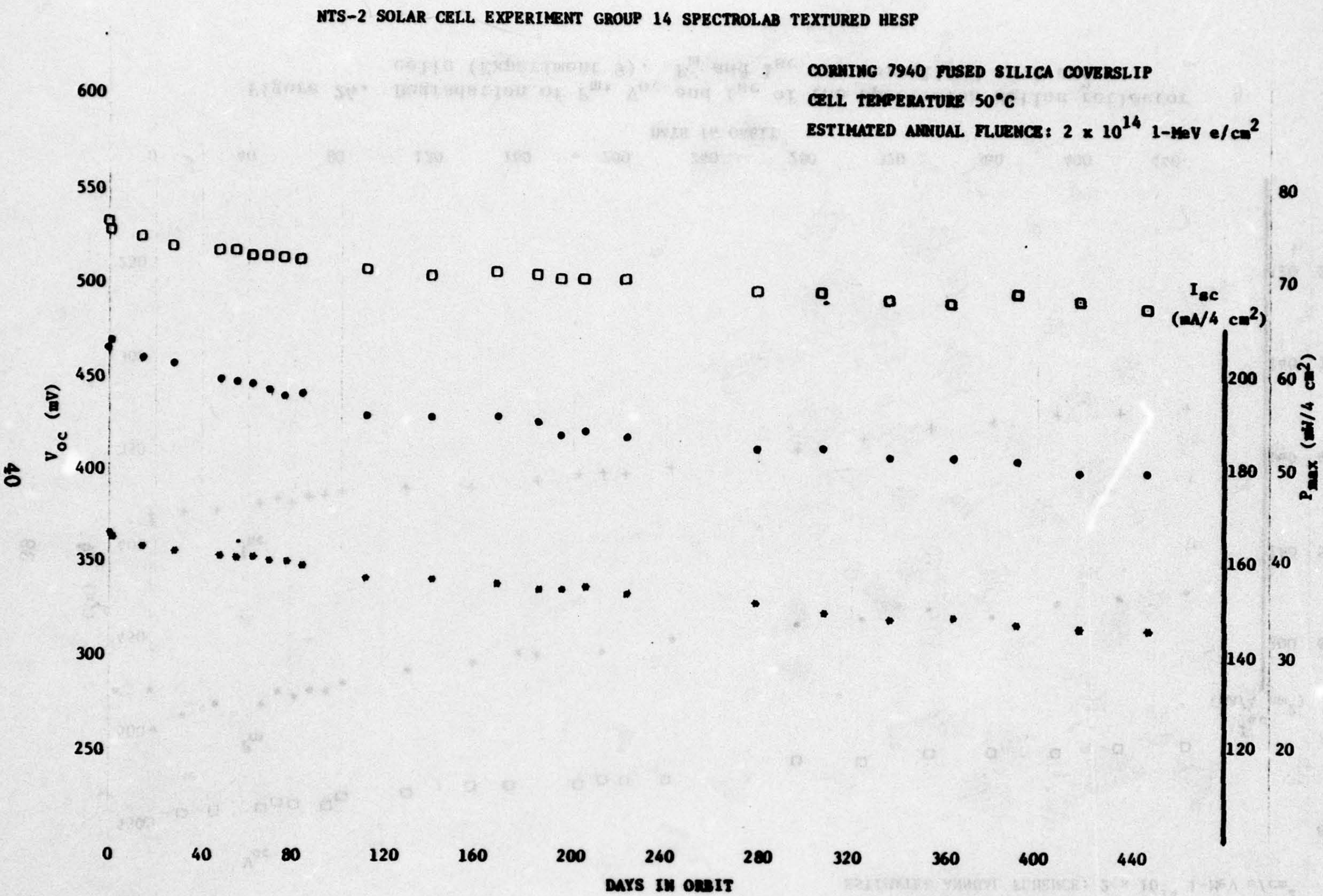

Figure 25. Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab HESP solar cell (Experiment 14). I_{sc} and P_m are normalized to 4 cm^2.

Table 5

NTS-2 SHORT-CIRCUIT CURRENT OUTPUT FOR SOLAR CELL EXPERIMENTS

		SHORT-CIRCUIT CURRENT OUTPUT (mA/4 cm^2)*			
EXPERIMENT NO.	CELL TYPE	SOLAR SIMULATOR	DAY 1 IN ORBIT	DAY 447 IN ORBIT	% LOSS DAY 1 TO DAY 447
1	OCLI Conv. 2 ohm-cm	135.4	136.5	112.5	17.6
2	Spectrolab Helios (NTS-2)	154.5	155.5	137.0	11.9
3	Spectrolab Text. Hybr., F.S.	155.6	154.0	136.2	11.6
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	151.0	149.6	137.5	8.1
5	Comsat Text. F.S., w/o filter	184.8	180.4	111.4	38.2
6	Comsat Text. F.S.	180.8	178.7	152.7	14.5
7	Solarex Vert. Junc.	158.4	160.5	118.1	26.4
8	Solarex Space Cell	155.9	158.8	-	100
9	Spectrolab Text. Helios Reflector	174.3	175.8	149.4	15.0
10	OCLI Violet, F.S.	165.1	164.3	138.5	15.7
11	Spectrolab HASP w/o diode	136.2	132.6	115.6	12.8
12	Spectrolab HASP w/diode	134.5	132.4	114.1	13.8
13	OCLI Conv., ESB	147.3	146.1	131.8	9.8
14	Spectrolab HESP	166.2	165.8	145.3	12.4
15	HRL AlGaAs	102.9	100.6	82.4	18.1

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

Table 6

NTS-2 OPEN-CIRCUIT VOLTAGE OUTPUT FOR SOLAR CELL EXPERIMENTS*

EXPERIMENT NO.	CELL TYPE	SOLAR SIMULATOR	DAY 1 IN ORBIT	DAY 447 IN ORBIT	% LOSS DAY 1 TO DAY 447
1	OCLI Conv. 2 ohm-cm	533	549	526	4.2
2	Spectrolab Helios (NTS-2)	527	546	503	7.9
3	Spectrolab Text. Hybr., F.S.	491	508	489	3.7
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	491	505	489	3.2
5	Comsat Text. F.S., w/o filter	533	555	517	6.8
6	Comsat Text. F.S.	533	549	522	4.9
7	Solarex Vert. Junc.	528	521	380	27.1
8	Solarex Space Cell	535	541	-	100
9	Spectrolab Text. Helios Reflector	550	545	507	7.0
10	OCLI Violet, F.S.	550	552	534	3.3
11	Spectrolab HASP w/o diode	552	559	535	4.3
12	Spectrolab HASP w/diode	523	523	488	6.7
13	OCLI Conv., ESB	488	490	463	5.5
14	Spectrolab HESP	533	528	486	8.0
15	HRL AlGaAs	914	895	873	2.5

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

Table 7

NTS-2 SOLAR CELL EXPERIMENTS

SUMMARY OF CHANGES IN PHOTOVOLTAIC PARAMETERS*

		PERCENT LOSS DAY 1 TO DAY 447		
EXPERIMENT NO.	CELL TYPE	MAXIMUM POWER	SHORT-CIRCUIT CURRENT	OPEN-CIRCUIT VOLTAGE
1	OCLI Conv. 2 ohm-cm	23.1	17.6	4.2
2	Spectrolab Helios (NTS-2)	22.3	11.9	7.9
3	Spectrolab Text. Hybr., F.S.	17.9	11.6	3.7
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	14.4	8.1	3.2
5	Comsat Text. F.S., w/o filter	44.2	38.2	6.8
6	Comsat Text. F.S.	21.1	14.5	4.9
7	Solarex Vert. Junc.	59.5	26.4	27.1
8	Solarex Space Cell	100	100	100
9	Spectrolab Text. Helios Reflector	22.0	15.0	7.0
10	OCLI Violet, F.S.	19.4	15.7	3.3
11	Spectrolab HASP w/o diode	20.4	12.8	4.3
12	Spectrolab HASP w/diode	23.0	13.8	6.7
13	OCLI Conv., ESB	19.0	9.8	5.5
14	Spectrolab HESP	22.1	12.4	8.0
15	HRL AlGaAs	14.0	18.1	2.5

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

Conclusions

The overall performance of the flight experiment and the quality of the data continue to be excellent. Several important conclusions which have been reached concerning the new cell technologies are listed below.

1. The Spectrolab Helios p^+ (K6) cell with an adhesive-bonded 0.0254 cm ceria microsheet coverslip is an excellent solar cell for the GPS natural environment. The Spectrolab textured hybrid cell with an FEP bonded 0.0152 cm "as-cut" quartz coverslip is equally satisfactory for this orbit.
2. There are three other types of silicon cells which can be classed as production cells, or ready for production, whose P_M exceeded the Helios (Exp. 2) and hybrid (Exp. 4) output. These are in ascending order of P_M: the Spectrolab textured HESP, no p^+, with adhesive-bonded 0.030 Corning 7940 coverslip; the OCLI violet cell, with an adhesive-bonded 0.030 cm Corning 7940 coverslip; and the Spectrolab textured Helios p^+, with a back surface reflector and an FEP bonded 0.030 cm as cut quartz coverslip.
3. The FEP Teflon bonded "as-cut" quartz coverslip gives very high cell power output, with no evidence of any problems, and performs as well as adhesive bonded uv filter Corning 7940 for radiation shielding and optical transmission.
4. The Hughes gallium-arsenide cell has the smallest degradation rate for P_M and V_{OC} of all cells.

Some unresolved findings which are of great importance and deserve further investigation are:

1. The annealing of V_{OC} and P_M in the gallium-arsenide cell during the first 80 days.
2. Thermal cycling effects in the vertical junction solar cell.
3. Unexpectedly large I_{sc} loss in a solar cell covered with adhesive-bonded Corning 7940 coverslip having no uv filter to protect against uv darkening of adhesive.

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